

The University of Chicago

THE FORMS AND MOTIONS OF THE SOLAR PROMINENCES

A DISSERTATION

SUBMITTED TO THE FACULTY OF THE OGDEN GRADUATE SCHOOL OF SCIENCE IN
CANDIDACY FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

(DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS)

BY

EDISON PETTIT

A Private Edition

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THE FORMS AND MOTIONS OF THE SOLAR PROMINENCES¹

BY EDISON PETTIT

INTRODUCTION

The following work is based on a study of solar prominences photographed with the Rumford spectro-heliograph of the Yerkes Observatory. The study covers both the plates already taken and a series made for special purposes.

In the beginning it was thought desirable to attempt to determine, if possible, the character of the movements and changes of form of prominences. With this in mind a preliminary survey was made of the already existing series of plates to discover any types which might prove interesting for study.

In all about four thousand plates were examined, all the interesting objects recorded, and the typical forms drawn. Very little material suitable for a study of the motions of the prominences was found, but the following types proved of interest.

1. *The "splash" type.*—This was always associated with the active type of sun-spot. No case was found not so associated. In all sixty-nine were recorded. Normally this type consists of broken spikes projecting radially from the spot, together with one or a pair of winglike prominences on either side, often raised into space, sometimes very unequal in dimensions. The prominence associated with the great spot of August, 1917, was typical of this form. As will afterward appear, the motion of these prominences, broken spikes, and loose knots of matter is into, not out from, the spot on the plates which I have measured. Occasionally a knot far removed from the spot may be found moving as though along lines of force into it. Generally, however, they are such filamentary bodies that apparently they cannot endure a long journey. The effect of "lines of force" as about a magnet is very suggestive when coupled with the fact of centripetal motion. In some cases these motions have been followed in detail, as will appear later.

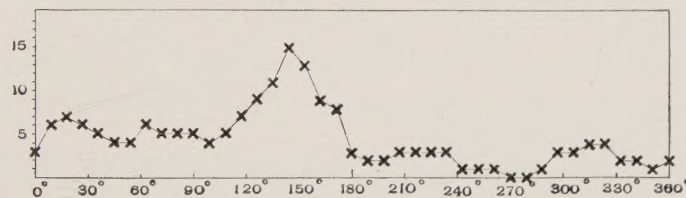


FIG. 1.—Distribution of the "splash" prominences in heliographic longitude for the period 1908 to 1920

The distribution of these splash prominences in heliographic longitude and latitude is shown in Figure 1. Obviously this is also the distribution of the great active spots associated with them over the same period, 1908–1920. Relatively few plates of the prominences were taken previously to 1908.

The distribution in latitude follows the usual sun-spot curve, but the distribution in longitude shows a sharp maximum in longitude 145°. The greater part of these prominences is found between longitudes 0° and 180°. Judging from this circumstance, this is the active hemisphere of the sun.

2. *"Tornado" or spiral prominences.*—These form a most interesting type. When perfectly developed, they are very small, generally 10'' or 15'' in diameter and 1' or 2' high. They appear like closely twisted rope or a fine screw. Plate XXVII shows two of these, the first taken by Slocum on October 15, 1910, and the second by the author on July 12, 1919. Such small objects are difficult to photograph since poor seeing entirely obliterates their true structure.

¹ Reprinted from *Publications of the Yerkes Observatory*, Vol. III, Part IV. Chicago: The University of Chicago Press, 1925.

Thirty cases of these tornado prominences are now available in the collection of negatives at the Yerkes Observatory. Assuming the top to be in rotation, the direction of rotation is clockwise in both hemispheres of the sun, since they all present the appearance of a right-handed screw, except in two cases where the prominence was bifurcated, the two branches rotating in opposite directions. The material was not sufficient to establish the presence or absence of lateral motion such as takes place in tornadoes on the earth.

3. *Eruptive prominences*.—This type probably needs definition. Under the classification of "eruptive prominences" have usually been placed metallic prominences, jets and prominences which rise a few seconds of arc and fall again to the chromosphere, and those which are torn apart by the action of a local attracting force. These I am not considering under this class. Only those prominences will be included which rise from the chromosphere and, projected in a more or less vertical direction, are dissipated into space at enormous altitudes. At the beginning of the work only three of these prominences had been observed in this series. One was observed by Fox on May 21, 1907; one by Slocum on March 25, 1910; and one by Lee on October 21, 1914. While it was found later that this material could be used, yet at the time this was not apparent.

THE APPARATUS

In order to follow an eruption it is necessary to develop the plates continuously. Hence every advantage must be taken of devices aimed to facilitate exposures at the telescope.

One cause of loss of time lay in the unstable prism support. This made it necessary to reset the second slit on the line after each exposure. Since the plate-holder had to be removed in order to do this, seventeen operations were required between each pair of exposures. To avoid this, a right-angled prism was inserted into the spectrum in the manner described by Hale and Ellerman in "Publications of the Yerkes Observatory," Vol. III, Part I.

Another cause of confusion lay in the lack of means of locating accurately the position of the prominence on the occulting disk. This was remedied by filing notches in the occulting disk every 10° from the east and west points. These imprinted themselves on the plate, and thus a prominence was readily located in the darkroom.

On account of the spread of the sky-spectrum, only one row of exposures could be put on a plate. To remedy this a focal-plane shutter was attached, making it possible to put two rows of exposures on a plate. By this means as many as eight or ten exposures could be put on a plate without removing it from the camera.

The driving-rod was provided with a stuffing-box and the protecting-shield raised so that it was not necessary to remove the rod for plates of the disk.

Several other modifications of the instrument were made to facilitate the exposures as much as possible and avoid any accidents which might delay the exposure or spoil the plate.

THEORY OF THE INSTRUMENT

The theory of the instrument has been given in detail in the publication referred to above. Some points, however, are of especial interest in connection with the study of the motions of the prominences. There is practically no distortion of the field, so that no correction has to be applied to observed motions on this account. Line-of-sight motions greater than about 30 km/sec. are sufficient to obliterate that part of a prominence having that velocity, from the plate.

The effect of wedge-slit was overcome by placing a small opposing lever at the end of the slit which habitually became too wide. By means of an adjustable screw this lever could be brought to bear on one jaw of the slit in such a way as to correct the wedge effect.

The error of setting the occulting disk is principally due to the fact that the telescope has a visual achromatic objective. Since the spectroheliograph works in the H line, the sun's disk appears about 5 inches out of focus. Hence, when setting the occulting disk, about $\frac{1}{8}$ inch of the image must overlap all around.

A little too much will produce serious sky fog, and too little will cut out the chromosphere. Sometimes a small drift due to clock-error may enter, but, since the whole exposure for one limb is only 99 seconds, this is not usually large enough to be noticeable.

When plates affected by faulty setting of the occulting disk are compared, several small stationary prominences are made to coincide, and the correction measured at the limb. This correction of course will always be positive.

MEASUREMENT OF THE PLATES

1. *The eruptive prominences.*—The height of an eruptive prominence at various stages of the eruption was measured by simply placing a glass scale over the plate radially to the limb and reading off the value. This was repeated with a steel millimeter scale as a check.

Generally speaking, no particular formation of a prominence can be followed throughout a series of exposures, consequently the mean height or apparent center of gravity of the object was chosen. Whenever a formation could be identified throughout a series of plates, it was used as the setting-point.

2. *Internal motions.*—The motion of knots and shreds was measured in the “blink” comparator with micrometer attached. This micrometer has two screws working cross-ruled reticles at right angles to each other. The screw value was found by comparison with the parallax machine to be $R=0.197$ mm, and is the same for both screws.

Orientation of the plates was somewhat handicapped by the sticking of one of the plate-carriers so that it could not be rotated in position-angle. On this account orientation was accomplished as follows. The plates to be compared were placed in the plate-holders with the dust-lines parallel (nearly) to the ways, glass side out. Since the telescope is driven in declination in order to give motion to the image on the spectroheliograph, these dust-lines are arcs of hour circles, indicating N.-S. Since the position-circle of the micrometer is fixed, the zero cannot be made to coincide with the north point, and hence the error was determined. The reading for the north point was generally about $87^{\circ}.5$. The east point was, of course, 90° less than this. A dust-line on the movable plate (the same dust-line was generally obtainable) was then brought into coincidence with the reticle line by rotating the holder and shifting the vertical lift-screw. The two images of the chromosphere were then made to coincide and this adjustment perfected by making small prominences and lumps on the chromosphere coincide exactly. Many small prominences are generally present, which remain fixed over long periods.

The displacement of a knot or filament from an earlier plate to the next later plate was then measured in position-angle and distance. Most of the points on the plates of the prominence of May 29, 1919, were measured with the movable wire only, three settings being made on the position-circle and on each point with the screw. An opposing spring was placed on the micrometer, however, after which it was only necessary to make half the settings with the movable wire.

On account of the rapid changes in the form of the objects measured, a high degree of accuracy was not attainable. Generally a range of twenty-five to thirty-five divisions on the micrometer head was satisfactory. On the other hand, the displacements to be measured were relatively large, so that this difficulty was not a serious one.

3. *Lateral motions.*—In some cases of lateral motions, later to be described, it became desirable to measure the displacements in rectangular co-ordinates, in which both screws of the micrometer were used. The orientation was performed as before described, but the measurement proceeded as follows. In order to make each measure independent of the cumulative errors of the one preceding, each plate was compared with the same plate, which we will call the “standard plate,” preferably the first plate of the series. An ink-dot was then made on the chromosphere as nearly under the midpoint of the lateral path of the prominence as possible. The reticle line parallel to the screw was then made tangent to the chromosphere at this point, and the circle read off. In all succeeding measures, this same angle, corrected for orientation, was used for the point of tangency. The origin of the fixed reticle lines was then set on this

point and the origin of the movable system was set on the prominence to be measured. The screws then read the co-ordinates. In some cases it was necessary to use the movable system for setting, as well as for measurement, on account of the limited field of the eyepiece.

PRELIMINARY OBSERVATIONAL DATA

It has already been shown by observers of eruptive prominences that the velocity of ascent increases with the height to which the prominence rises, and consequently with the time in a general way, but no one seems to have obtained the data for fixing the detailed facts of the motions. The great prominence of May 29, 1919, offered an unusual opportunity for studying the motion in detail, on account of its more leisurely ascent and the height which it reached, and the prominence of July 15 gave a means of checking the results so obtained. The general facts and observational data about these two prominences have been given in detail in the *Astrophysical Journal*, 50, 206-219, 1919. We will confine the discussion at present to the vertical motions of eruptive prominences.

Sections 1 and 2 of Table II show the data for these prominences measured as before described, and the measures of the height as ordinates against the time as abscissas are plotted in Figure 2, Numbers 1 and 2. These results are obviously best represented by broken straight lines—in fact, remarkably well.

We must conclude that for these two prominences the motion was uniform over a period of time, after which it increased suddenly, but continued to be uniform at the greater velocity, as though an impulse had been given to it at that point. Table I exhibits a comparison² of the observed data for these two prominences and the data computed from the gravitational theory of projected bodies.

TABLE I

HEIGHT OF PROMINENCE ABOVE SUN	VELOCITY OF ASCENT	ΔV	RISE AT THIS VELOCITY	THEORETICAL MAXIMUM HEIGHT AT THIS VELOCITY	OBSERVED DURATION (CONST. V.)	THEORETICAL DURATION (DIMIN. V.)
The Prominence of May 29						
km	km/sec.	km/sec.	km	km	min.	min.
150,000	5.5	5.5	50,000	83	164	0.5
200,000	14.7	9.2	119,000	665	133	1.5
319,000	27.9	13.2	91,000	3,010	57	3.6
410,000	60.0	32.1	230,000	17,059	63	9.5
The Prominence of July 15						
200,000	37.0	?	294,000	4,211	43	3.8
294,000	163.9	126.9	426,000	111,753	47	23.6

For the computation of this data the following formulae are adapted (*loc. cit.*):

$$H = s_1 - s_0 = \frac{V_0^2 s_0^2}{2gR^2 - V_0^2 s_0}, \quad (1)$$

$$T = \frac{A \frac{\pi}{2} - AB + C}{D}, \quad (2)$$

$$t = \frac{A \sin^{-1} \left[\frac{2s - s_1}{s_1} \right] - AB + C - \sqrt{s_1 s - s^2}}{D}, \quad (3)$$

² *Astrophysical Journal*, 50, 214, 1919.

where

$$A = \frac{s_1}{2}, \quad B = \sin^{-1} \left[\frac{2s_0 - s_1}{s_1} \right], \quad C = \sqrt{s_1 s_0 - s_0^2}, \quad D = R \sqrt{\frac{2g}{s_1}}.$$

g = acceleration of a falling body at the sun's surface (0.27 km/sec.)

H = "theoretical maximum height attained" measured from sun's surface

R = radius of the sun (695,553 km)

s = distance at any instant from the sun's center

s_0 = distance from the sun's center at the time when the velocity V_0 begins (measured from the break in the graph of the heights of the prominence)

s_1 = "theoretical maximum height attained" measured from the sun's center

T = time required to attain height H ("theoretical duration")

t = time required to attain distance s from sun's center

V_0 = "velocity" observed, measured from the plot

In these formulae the positive direction of the axes is taken upward and angles are in radians. It will be noted that the gravitational theory is not sufficient even to approximate the observed facts over a short period.

The prominence of September 8, 1919, and the one observed by Lee on February 19, 1920, also show the characteristics of motion found in those of May 29 and July 15, 1919.

THE COLLECTED OBSERVATIONAL DATA

As it appeared that this peculiarity of motion of eruptive prominences might be characteristic of all eruptions, an investigation of all available published data was made to determine the facts of the case. All cases of observed eruptions where four or more measures of the height were obtained during the ascent were collected, and plotted uniformly with G.M.T. as abscissas and the height in thousand kilometers as ordinates. Generally the data gave local or standard time of observation and the height in seconds of arc. These were converted by the proper formulae. In some cases of spectroheliographic observation the plates or prints were remeasured, for reasons stated in the appended notes. Eighteen cases besides those already mentioned were found, making in all, at present, twenty-four cases of eruptive prominences for which the data are sufficient for the study of their motion. Of these, eleven are spectroheliographic results.

DISCUSSION OF THE COLLECTED OBSERVATIONAL DATA

From an examination of the plots of the observations given in Figures 2-5, one can hardly avoid the conclusion that in every case so far observed the motion of ascent obeys the principle found in the prominence of May 29, 1919, namely, that the motion is always uniform, affected at intervals by sudden increases, as though an impulse had been given to the prominence.

The validity of this method of treating the observations can hardly be questioned, for each observation itself is not definitive, and in this kind of measurement is subject to considerable error as compared, say, to measurements for positions of stars. The actual velocities attained, then, are represented by the slopes of these straight lines, and not by $\delta h / \delta t$ between successive observations. Indeed, two successive velocities might be 60 km/sec. and -10 km/sec. and still the plotted observations could fall satisfactorily near the mean line, if δt were not too great. Take, for example, the prominence of September 19, 1893,³ for which Fényi gives the velocities reduced from $\delta h / \delta t$, shown in Table III on page 212.

To find any law of motion applicable to these data would be quite discouraging, but the difficulty lies in the treatment of single observations as definitive, which is far from the case. Referring to the graph for this prominence (Fig. 4, No. 17), it will be seen how well the observations of this prominence follow the

³ *L'Astronomie*, 13, 173, 1894.

TABLE II
COLLECTED DATA ON ALL PUBLISHED MEASURES OF ERUPTIVE PROMINENCES

Identity and Remarks	G.M.T. of Observation	Height in Thousand Kilometers	Identity and Remarks	G.M.T. of Observation	Height in Thousand Kilometers
1. May 29, 1919. Observed by Pettit at the Yerkes Observatory. Spectroheliograph. <i>Astrophysical Journal</i> , 50, 209, 1919. Mean height of the floating cloud is given. $V=5.5, 14.7, 27.9, 60.0$ km/sec.	1 ^h 17 ^m 09 ^s	150	4. Feb. 19, 1920— <i>Continued</i>	7 ^h 25 ^m 35 ^s	319
	36 25	150		33 40	322
	41 16	150		35 11	326
	51 49	153		55 25	334
	2 35 21	163		57 01	341
	41 44	170		8 15 30	387
	49 39	170		18 50	387
	56 56	175	5. October 21, 1914. Observed by Lee at the Yerkes Observatory. Spectroheliograph. No measures published. <i>Astrophysical Journal</i> , 41, 168, 1915. $V=6.7, 22.0, 42.8$ km/sec.	3 17	106
	4 09 40	175		54.5	123
	19 32	200		56.5	129
	31 03	210		4 17	144
	38 12	220		18.7	145
	46 49	225		49.2	186
	5 13 59	250		50.7	189
	32 41	265		57.5	199
	40 39	275		58.7	204
	56 36	285		5 05.7	220
	6 14 12	305		07.5	234
	23 34	310		33.5	293
	32 18	322		35.5	292
	42 00	335		2 54.9	38
	53 22	360		4 14.7	53
	7 08 49	388		16.7	68
	19 31	410		56.1	103
	57 22	545		57.9	148
	8 23 29	640		5 10.6	174
2. July 15, 1919. Observed by Pettit at the Yerkes Observatory. Spectroheliograph. <i>Astrophysical Journal</i> , 50, 211, 1919. Settings were made on a ropelike structure enduring throughout the eruption. $V=37.0, 163.9$ km/sec.	3 08 02	200		43.0	276
	28 48	250		45.0	287
	35 49	263		55.4	295
	43 59	278		57.7	295
	51 56	315	7. May 21, 1907. Observed by Fox at the Yerkes Observatory. Spectroheliograph. <i>Astrophysical Journal</i> , 26, 155, 1907. $V=7.5, 37.5, 64.2$ km/sec.	4 02	169
	4 01 11	400		52	190
	07 19	460		5 01	206
	15 57	548		35	287
	23 39	620		37	294
	33 57	720		43	317
3. September 8, 1919. Observed by Pettit at the Yerkes Observatory. Spectroheliograph. Not published. Settings made on the center of the cloudlike head. $V=3.7, 25.6$ km/sec.	2 35 32	85		44	272
	3 01 52	93		44.5	272
	35 59	95		52	307
	38 37	97		53	305
	46 07	101		55	311
	46 42	103		57	301
	4 21 22	116		59	303
	34 12	128	8. February 18, 1908. Observed by Evershed at the Kodaikanal Observatory. Spectroheliograph. <i>Astrophysical Journal</i> , 28, 79, 1908. See also <i>Bulletins of the Kodaikanal Observatory</i> , 2. Only group measures are given. Half-tone cuts were remeasured in order to give more points. $V=3.3, 29.3$ km/sec.	2 53	58
	37 12	131		4 08	69
	6 16 10	286		24	77
	23 30	301		31	77
	41 10	321		5 35	96
	50 21	348		43	96
September 8, 1919, continued. Settings made on a condensation near the middle of the prominence. $V=25.6$ km/sec.	6 16 10	150		9 00	113
	24 12	160		06	113
	41 10	193		10 35	144
	50 10	210		40	154
	7 01 07	225		11 41	234
4. February 19, 1920. Observed by Lee at the Yerkes Observatory. Spectroheliograph. Not published. Center of the crest measured. $V=10.6, 18.6, 41.7$ km/sec.	08 05	230		47	261
	3 58 40	110	9. May 26, 1916. Observed by Evershed at the Kodaikanal Observatory. Spectroheliograph. <i>Bull. of the Kodaikanal Observatory</i> , 3, No. 55, Plate IV. A secondary eruption from the crest of the prominence made it necessary	12 02	290
	4 48 00	144		11	301
	56 30	148		2 36 12	102
	58 20	152		51 47	166
	5 22 50	171		06 29	220
	24 25	175		16 25	322
	31 50	186		20 40	372
	34 50	186		26 40	440
	56 55	205			
	58 50	209			
	7 24 15	311			

TABLE II—Continued

Identity and Remarks	G.M.T. of Observation	Height in Thousand Kilometers	Identity and Remarks	G.M.T. of Observation	Height in Thousand Kilometers
9. May 26 1916—Continued to remeasure the cuts in order to insure continuity of the point measured. $V=64.2, 191.7, 316.6$ km/sec.	3 ^h 33 ^m 19 ^s 39 34	524 643	17. September 19, 1893. Observed by Fényi at the Haynald Observatory. Visual. <i>L'As-tromie</i> , 13, 173, 1894. <i>Mem. Spett. Ital.</i> , 23, 29, 1894. $V=119.4, 375.0, (250.0)$ km/sec.	2 ^h 21 ^m 05 ^s (21 51) 22 37 23 36 24 25 25 19 26 15 27 16 28 23	268 (256) 278 286 296 319 338 344 362
10. May 31, 1894. Observed by Deslandres at the Paris Observatory. Spectroheliograph. <i>Comptes Rendus</i> , 124, 172, 1894. $V=13.8, 54.4$ km/sec.	1 55 4 18 51 5 31	103 220 323 458		9 15 00 10 17 59 18 29 18 59 19 30 20 01 20 33 33 45 34 31 35 20 36 09 37 03 41 33 42 45 †48 49 23 ‡52 04 55 21 11 06 31 09 57 11 20 12 44 24 51 38 04 38 57 39 24	88 151 148 156 160 150 154 266 276 288 297 309 369 364 388 404 445 470 286 317 330 282 255 222 193 193 107
11. March 25, 1895. Observed by Hale and Ellerman at the Kenwood Observatory. Spectroheliograph. <i>Astrophysical Journal</i> , 1, 433, 1895. $V=49.0, 119.0, 202.0$ km/sec.	*15 40 16 24 30 *36 48	87 216 259 303 450	18. December 24, 1894. Observed by Fényi at the Haynald Observatory. Visual. <i>Astrophysical Journal</i> , 1, 213, 1894. $V=15.5, 144, 144$ km/sec.		
12. August 16, 1885. Observed by Trouvelot at the Meudon Observatory. Visual. <i>Comptes Rendus</i> , 101, 475, 1885. $V=53.3, 89.2$ km/sec.	9 16 10 21 37 38 42 47 53 58 11 00 02 04 11	172 213 264 278 290 298 320 341 352 361 373 416			
13. September 6, 1888. Observed by Fényi at the Haynald Observatory (Kaloosa). Visual. <i>Pub. of the Haynald Observatory</i> , 1, 119, 1888. $V=2.2, 83.3, 175.5$ km/sec.	4 25 50 52 55 59 5 03	15 18 33 43 68 110			
14. October 6, 1890. Observed by Fényi at the Haynald Observatory. Visual. <i>Pub. of the Haynald Observatory</i> , 1, 131, 1888; and <i>Comptes Rendus</i> , 111, 725, 1890. $V=40.0, 70.0, 223.3, (56.7)$ km/sec.	0 02 07 10 20 12 50 19 25 †21 23 27 29 40 33	40 50 66 76 100 123 148 206 225 236	19. September 30, 1895. Observed by Fényi at the Haynald Observatory. Visual. <i>Astrophysical Journal</i> , 3, 193, 1896. $V=400$ km/sec.	‡10 00 ‡11 14 22 15 11 16 03 16 57 17 50 19 02 20 11 §21 00 29 20 30 13 46 39	43 174 342 371 380 407 430 446 498 357 380 388 142
15. May 5, 1892. Observed by Fényi at the Haynald Observatory. Visual. <i>Pub. of the Haynald Observatory</i> , 2, 131, 1892. $V=81.7, 233.3$ km/sec.	10 39 11 01 02 45 05 09 09 13 25	102 209 231 269 275 295 299 350 388	20. June 1, 1900. Observed by Fényi at the Haynald Observatory. Visual. <i>Astrophysical Journal</i> , 12, 215, 1900. Height of the vertex and base of the floating cloud were observed. Mean height is given here. $V=242$ km/sec.	2 14 08 14 41 15 16 15 52 16 29 17 16 18 04 || 18 55	159 177 177 186 203 213 225 227
16. September 20, 1893. Observed by Fényi at the Haynald Observatory. Visual. <i>L'As-tromie</i> , 13, 174, 1894. <i>Mem. Spett. Ital.</i> , 23, 30, 1894. $V=400$ km/sec.	9 08 13 09 04 09 57 10 52 11 51 12 56 14 07 15 18	353 367 390 414 435 446 482 501	21. August 24, 1893. Observed by Sakora at the Charkow Observatory. Visual. <i>Mem. Spett. Ital.</i> , 23, 201, 1894. $V=22.5$ km/sec.	21 19 22 01 20 23 21	10 64 95 79

* Visual estimate.

† Time uncertain.

‡ Micrometer measure. Probably affected by distortion.

§ Uncertain.

|| "Approaching dissolution" noted here.

TABLE II—*Continued*

Identity and Remarks	G.M.T. of Observation	Height in Thousand Kilometers	Identity and Remarks	G.M.T. of Observation	Height in Thousand Kilometers
22. November 16, 1892. Observed by Tacchini at Rome. Visual. <i>Mem. Spett. Ital.</i> , 22, 9, 1893. $V=4.4, 6.6, 28.3, 57.2, 115.0$ km/sec.	8 ^h 10 ^m 00 ^s	94	23. June 11, 1895— <i>Continued</i> <i>Astronomical Journal</i> , 15, 112, 1895. Coit used the mean value of the sun's apparent diameter in reducing the observations; the values given here have been reduced using the <i>Ephemeris</i> value for the date. $V=7.8, 136.1, 58.7$ km/sec.	7 ^h 59 ^m 18 ^s	122
	40	104		8 00 18	131
	9 13	113		01 18	145
	54	124		03 03	154
	10 40	142		06 58	179
	11 05	152		12 00	185
	50	201		14 00	195
	12 03	288		17 18	203
	10	.....		19 28	212
	14	247		27	77
	29	307		47	59
	37	332	24. May 23, 1915. Observed by Evershed at the Kodaikanal Observatory. Spectroheliograph. <i>Mem. Kod. Observatory</i> , 1, Part II, 1917. No measures published. $V=70.8$ km/sec.	3 04	143
	42	367			
	43	382			
	44	382			
	45	382			
23. June 11, 1895. Observed by Coit at the Boston University Observatory. Visual.	7 17	54		18	206
	36	63			
	55 03	86			
				52	348

law of uniform motion affected by sudden increases of velocity. Velocity 3, in Table III, was computed on a break in the line, and so does not agree with any on the list. Velocities 5 and 6 are doubtless discordant on account of fading of the crest of the prominence. Applying the slope of the line, the actual velocities are only three in number, viz., 119, 375, and (250) km/sec.

TABLE III

No.	km/sec.	No.	km/sec.
1.....	114.6	5.....	339.6
2.....	126.1	6.....	103.9
3.....	214.0	7.....	249.1
4.....	406.0		

Pringsheim⁴ uses Fényi's published velocities of the prominence observed on October 6, 1890, to substantiate the statement that the velocities of eruptive prominences "undergo very irregular changes in direction and value." An examination of the plot (Fig. 4, No. 14) reveals no such irregularity, with the possible exception of the last two measures which are doubtless affected by fading.

This fading of the prominence is one of several phenomena accompanying an eruption which, in visual work, may produce a large uncertainty in the interpretation of the velocities at the end of the ascent. The rapidity of the fading has been noted by many observers. Thus Fényi says, speaking about the prominence of June 1, 1900 (for graph see Fig. 5, No. 20):

Approaching dissolution was noted during the last transit; the smaller portions were invisible, and the larger somewhat faint and diffuse, unless probably this was the effect of a temporary haziness of the sky. Three minutes later the entire brilliant prominence had disappeared; no trace could any longer be seen, even far above the chromosphere.⁵

The same circumstances have been noted frequently by observers with the spectroheliograph. Generally, it seems, the duration of the fading is only a matter of a few minutes.

That a prominence may fade in part and the remainder continue to ascend is well shown in the prominence of December 24, 1894, observed by Fényi (Fig. 4, No. 18). Here, evidently, the detached portion of

⁴ *Physik der Sonne*, p. 177.

⁵ *Astrophysical Journal*, 12, 217, 1900.

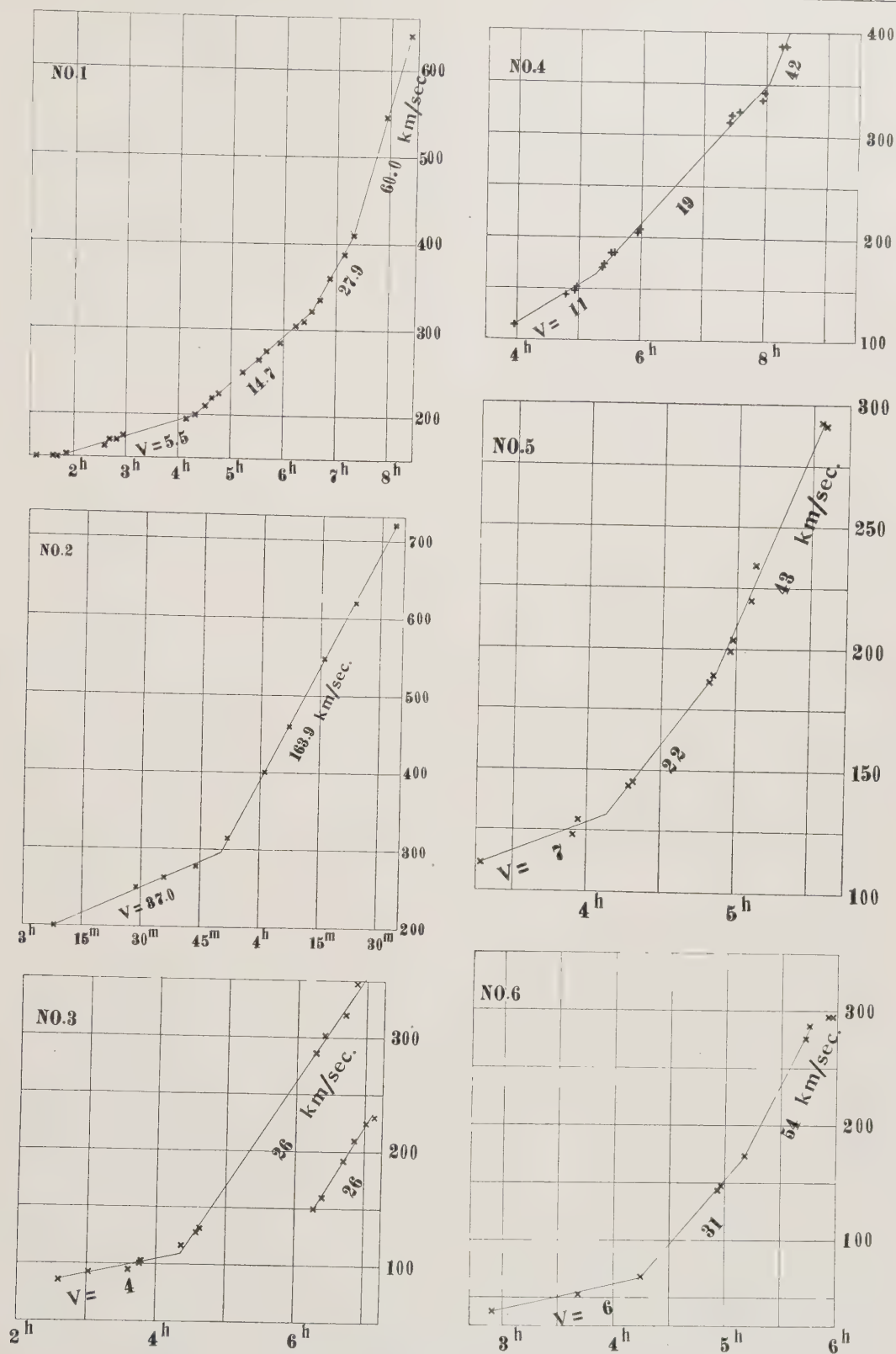


FIG. 2.—Motions of the eruptive prominences of (No. 1) May 29, 1919; (No. 2) July 15, 1919; (No. 3) September 8, 1919; (No. 4) February 19, 1920; (No. 5) October 21, 1914; (No. 6) March 25, 1910. The abscissas are the times of observation (G.M.T.), and the ordinates are the heights of the prominence in thousand kilometers.

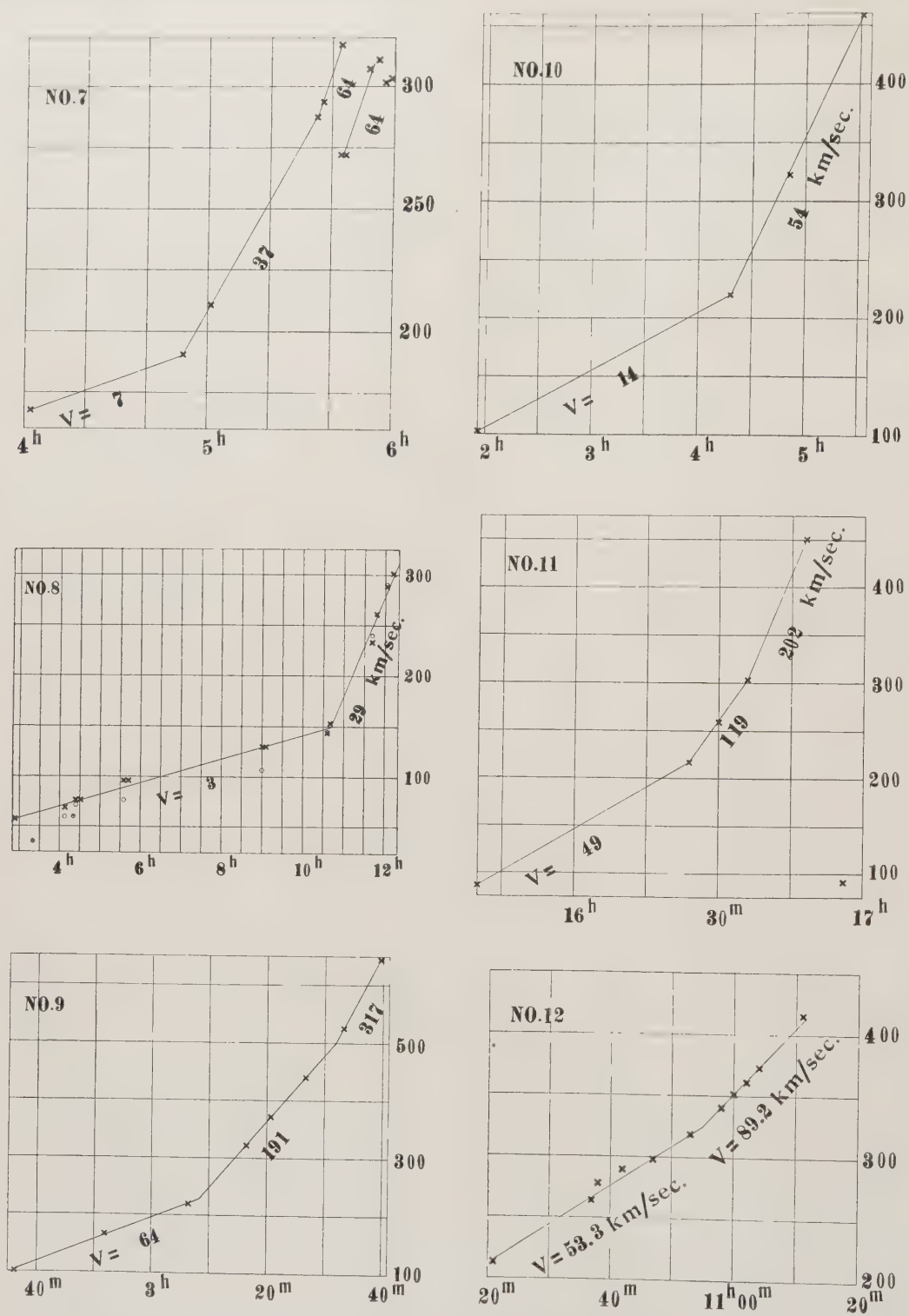


FIG. 3.—Motions of the eruptive prominences of (No. 7) May 21, 1907; (No. 8) February 18, 1908; (No. 9) May 26, 1916; (No. 10) May 31, 1894; (No. 11) March 25, 1895; (No. 12) August 16, 1885. The abscissas are the times of observation (G.M.T.), and the ordinates are the heights of the prominence in thousand kilometers.

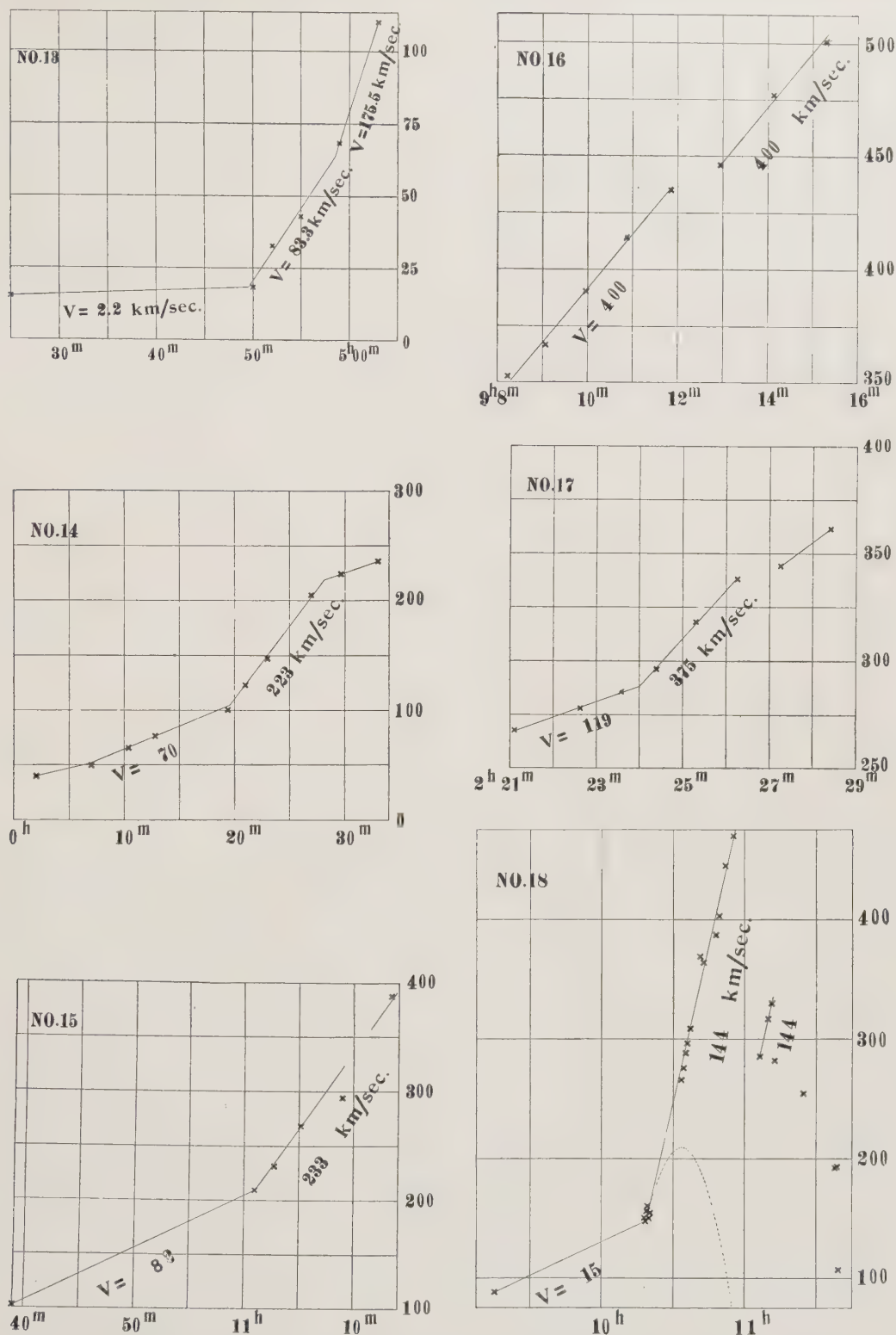
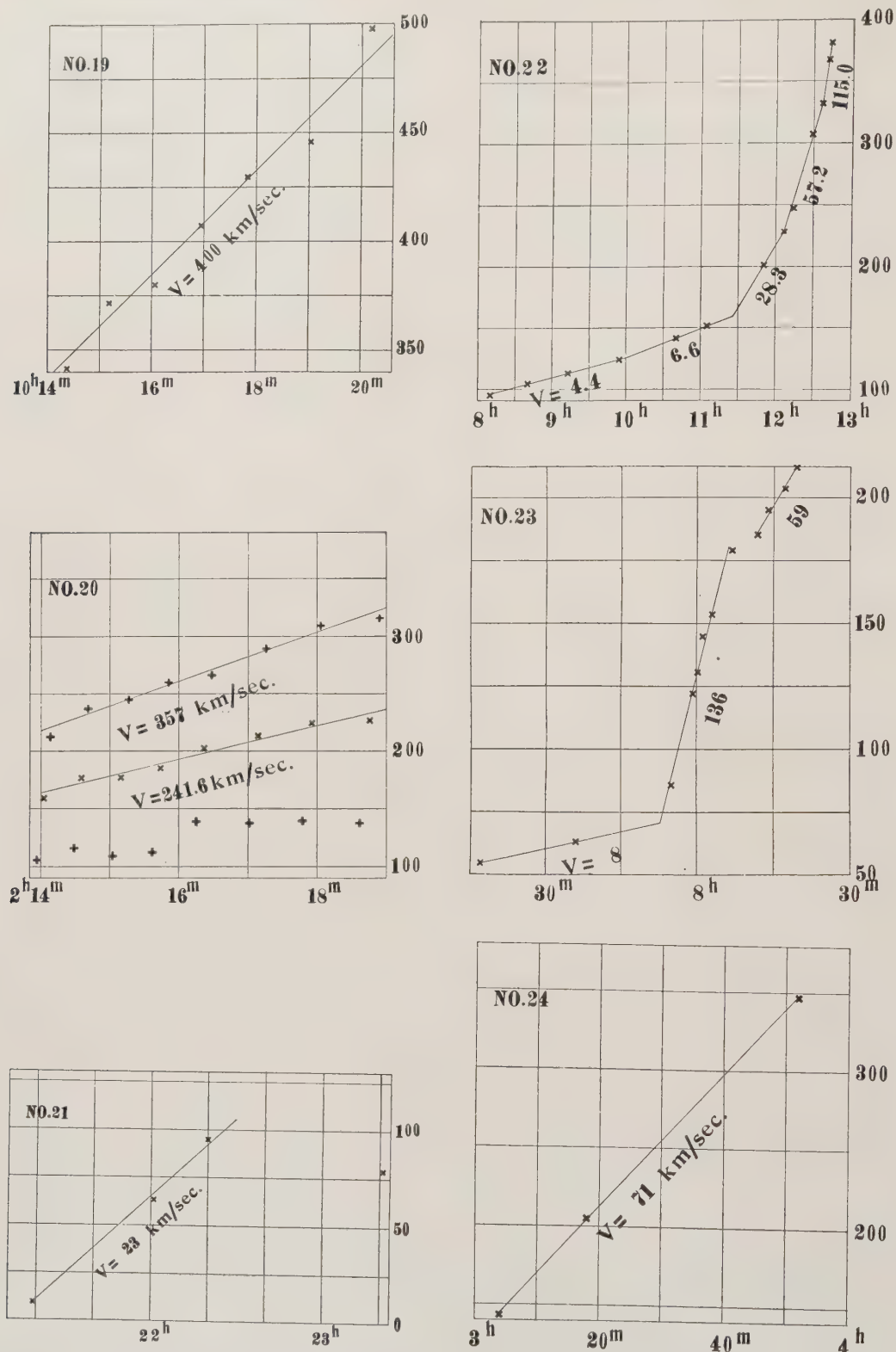


FIG. 4.—Motions of the eruptive prominences of (No. 13) September 6, 1888; (No. 14) October 6, 1890; (No. 15) May 5, 1892; (No. 16) September 20, 1893; (No. 17) September 19, 1893; (No. 18) December 24, 1894. The abscissas are the times of observation (G.M.T.), and the ordinates are the heights of the prominence in thousand kilometers.



the curve is a point lower down, rising after the prominence has been decapitated by fading. Hence the duration of fading must have been less than 10 minutes—the time between the observations on the two portions of the plot. The same phenomenon is apparent in his observations of the prominence of September 20, 1893 (Fig. 4, No. 16). Fox's prominence observed with the spectroheliograph on May 21, 1907 (Fig. 3, No. 7), is also of this class.

Fényi's prominences of October 6, 1890, and September 19, 1893 (Fig. 4, Nos. 14 and 17), seem to show indications of negative impulse or secondary eruption at the end of the ascent. Coit's prominence of June 11, 1895 (Fig. 5, No. 23), is the finest example of this class of phenomena. The nature of the action at the end of the eruption just after dissolution sets in is very uncertain and difficult to interpret without the aid of photography.

The effect of a secondary eruption is seen in Evershed's prominence of May 26, 1916, where a fountain of matter is ejected from the principal body after the prominence has reached a considerable height.

In his analysis of his observations on the prominence of June 1, 1900, Fényi gives the following data on the velocity of the crest:

TABLE IV

km/sec.	km/sec.
546	471
231	423
371	138
187	

From the plot (Fig. 5, No. 20) it will be seen that a straight line represents both the mean and the crest velocities very satisfactorily.

Fényi says:

I must state in regard to the velocities of ascent in the fourth column that no safe conclusions can be drawn from their differences, as they are the result of the uncertainty of the individual measures from which the figures were calculated. On trying to smooth out the data graphically I found that, if corrections of at most 0.6 sec. are applied to the time of transit, an entirely uniform ascent with constant velocity is obtained.

Such corrections are entirely justified by numerous transits of prominences, for it is not unusual for a single measure to differ from the mean of many transits by more than 0.5 sec. The assumption of uniform motion is unjustified, however, as the prominence is without doubt under the influence of gravity, and it must therefore sink at the time it is rising, unless it is impelled upward by some quite problematical continuous force. I have reduced the observed altitudes on the assumption of constant gravity with an acceleration of 270 meters, and again sought to smooth them out graphically. I found that the observed times of transit would require a correction of 0.7 sec. in only one case in order to be in full agreement with this assumption. Hence it appears that the above observations, despite the capricious ascent, are by no means inconsistent with the assumption that the prominence is a mass of hydrogen projected from the sun, which rises above the chromosphere with the velocity of empty space and is under the influence of gravity alone.⁶

Now the velocity is 354 km/sec. at a height of 218,000 km above the sun. This is over half the parabolic velocity, and since the observations cover a period of only 5 minutes, the straight line approximates the parabola very closely over this short interval. He admits that the straight line represents the observations just a little better, however. Had the same reasoning been applied to a more slowly moving or longer enduring prominence the case would have been more evident.

Fényi's prominence of December 24, 1894, the duration of which was two hours, is one of the finer examples exhibiting the characteristics of uniform motion broken by impulses. When we take the prominence at the first break, and apply the general gravitational formulae of page 208 (Nos. 1, 2, and 3) we have:

$s_0 = 845,553$ km	$T = 14^m 28^s$	$C = 227,469$
$V_0 = 144.4$ km/sec.	$A = 453,373$	$D = 536.76$
$H = 61,193$ km	$B = 1.0450$	$s_1 = 906,746$ km

⁶ *Astrophysical Journal*, 12, 216, 1900.

The following table was then computed from formula 3.

TABLE V

<i>s</i>	<i>t</i>	<i>s</i>	<i>t</i>
km		km	
845,553.....	0 ^m 00 ^s	906,746....	14 ^m 28 ^s
865,553.....	2 33	795,553....	14 51
885,553.....	5 53		

Here *t* is computed from the time the velocity began, namely, 10^h19^m G.M.T., and *s* from the center of the sun. From this data the dotted portion of the curve was plotted (Fig. 4, No. 18). One would hardly say that this prominence has been rising "with the velocity of empty space and under gravity alone." In fact, with many of the prominences it is impossible to represent the curve under gravity on the scale on which the observations are plotted, on account of the small dimensions of the parabola.

LATERAL MOTIONS

I am here using the term "lateral motions" to mean motions of prominences which rise from the sun's surface, and, passing over a trajectory, generally re-enter the chromosphere. Unfortunately, the observational data with detailed measures are rather scanty. None are to be found in the literature, perhaps on account of the relatively small size of the objects involved. Sufficient data were secured in only two cases to give anything like a life-history of such phenomena. Like the great eruptions, these laterally moving prominences endure only a short period of time with high velocities; but, unlike them, they disappear, apparently, not by fading away, but by bodily re-entering the chromosphere—like water poured into a pond. A number of others have been observed with the spectroheliograph, and while the data are not sufficient to warrant analysis here, the description of the two given is typical of all.

1. *The "sigma" prominence of September 23, 1919.*—This prominence (see Plate XXVIII) as photographed in the early morning would have been classified as quiescent. A small streamer leaving one side (exposure 1) entered the chromosphere at a point about 100,000 km distant. Toward noon the whole prominence seemed to rise slightly and lean violently toward the point above indicated, as if it were being torn from its anchorage in the chromosphere. By half-past one the number of streamers had increased to five, and the whole body began to disintegrate. The crest was torn away and, traversing a trajectory, entered the chromosphere 225,000 km from the starting-point for the particular knot measured. This knot, which was the most brilliant part, was always connected to the point of attraction by long streamers which themselves followed a somewhat shorter orbit of similar shape. The action was much like the cracking of a whip, the end swinging out and going beyond the path followed by the flexible body. Thirteen exposures (Plate XXVIII, Nos. 3–15), during the principal part of the action, were measured in *X* and *Y* co-ordinates with the "blink" comparator and micrometer. These measures were reduced to thousand kilometers and plotted to scale (Fig. 6, No. 1). The direction of the motion was toward the left, as indicated by the arrow. The first three observations (at the right) were made while the knot was still attached to the prominence, and are indicated by the dotted line. Probably they are not comparable with the others since the knot was not in free motion at the time.

While the trajectory is fairly represented by the ellipse, yet perhaps it is as well represented by a modified form of curve.

The plotted points were projected on this mean line of motion and their distances from the first point, which represents the beginning of the motion, were measured off along the curve. These measures were then plotted against the time of observation, as before in the study of the great eruptions. Plot 2 of Figure 6 represents this curve. It is very apparent that the law of motion here is the same as that followed by the eruptive prominences already discussed, and that the velocity (75.8 km/sec.) is of the same order.

2. *The "rocket" prominence of October 6, 1919.*—The early history of this prominence is very similar to that already described for the "sigma" prominence until the motion began. A piece was torn off bodily from the prominence, on the side opposite the streamers, and, without any visible connection with the chromo-

sphere, traversed a trajectory like a stone thrown from a catapult, and entered the chromosphere 150,000 km away. Plate XXIX shows twelve exposures during the period of activity.

Eleven plates were measured in X and Y co-ordinates and plotted to scale (Fig. 6, No. 3). The astonishing thing is that the trajectory is a circle of radius 73,500 km from a point 17,000 km above the chromosphere. The center of the circle is the empty cross. The arrow represents the direction of motion.

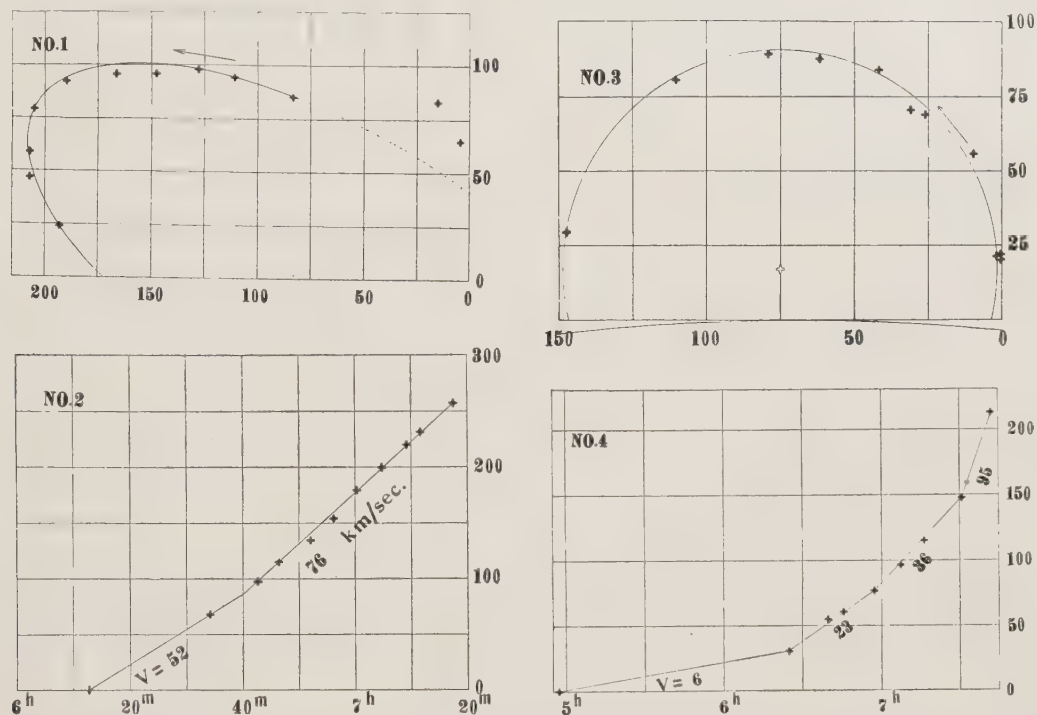


FIG. 6.—Trajectories of the prominences of (No. 1) September 23, 1919; (No. 3) October 6, 1919. Motions of the prominences of (No. 2) September 23, 1919; (No. 4) October 6, 1919. The abscissas of Nos. 1 and 3 are in units of thousand kilometers, and of Nos. 2 and 4 are times of observation (G.M.T.). The ordinates are in units of thousand kilometers.

The plotted points were projected on the circle and their distances from the beginning of the motion measured as before. The plot of these measures against the times of observation is given in plot 4, Figure 6. The data in this case are not conclusive, since a smooth curve represents the measures about as well as the broken line. About double the number of observations would be required to decide the question. Table VI gives the measures for these two prominences.

TABLE VI

	EXPOSED AT G.M.T.	IN UNITS OF 1000 KM				EXPOSED AT G.M.T.	IN UNITS OF 1000 KM		
		X	Y	Distance Trav- ersed			X	Y	Distance Trav- ersed
1. September 23, 1919. Observed by Pettit. Spectroheliograph. The "sigma" prominence.	6 ^h 00 ^m 52 ^s	0.0	58.5	.....	2. October 6, 1919. Ob- served by Pettit. Spec- troheliograph. The "rocket" prominence.	4 ^h 39 ^m 21 ^s	1.7	20.3	.....
	04 19	4.7	64.2	0.0		49 50	0.2	21.9	0.0
	12 45	15.0	82.9	68.0		57 12	0.6	21.5	0.0
	34 07	83.4	85.5	68.0		6 24 34	9.9	55.8	34.1
	42 32	110.9	94.2	97.6		39 27	26.2	68.8	54.8
	46 20	127.7	98.2	115.0		45 16	31.0	70.3	59.7
	52 05	147.7	96.1	134.5		57 05	46.9	83.8	76.5
	56 09	166.1	95.7	154.0		7 07 08	61.9	87.4	96.7
	7 00 19	189.9	92.4	179.0		16 02	79.1	88.9	114.6
	04 45	205.3	79.1	199.5		30 26	110.1	80.3	147.5
	09 05	207.4	58.7	220.0		41 53	147.6	29.4	213.0
	11 48	207.5	47.0	231.0					
	17 30	193.5	24.1	257.0					

INTERNAL MOTIONS

The question of the character of the motions relative to the forces acting may be studied indirectly by observing the motions of knots and markings. Such data are not so reliable as that just described, but are used here as correlative evidence.

It would be of interest to know whether the streamers, loops, and knots actually indicate the direction of movement of matter in the prominence, and whether the matter is moving into or out from the chromosphere. With this idea in mind nine prominences were measured in the "blink" comparator in the manner previously described.

Generally speaking, a given knot or marking will endure only over two or three plates, occasionally more, but generally losing its identity very soon. Experience in this sort of work shows the desirability of securing plates at approximately 2-minute intervals in order to follow the kaleidoscopic changes.

The prominence of May 29, 1919, proved especially rich in such points, and in this prominence alone 333 points were measured and the velocities reduced from the observed displacements. Plates XXX and XXXI represent this prominence in five stages of the eruption.⁷ Figures 7 and 8 are pantograph sketches of Plates XXX and XXXI with velocity vectors representing the observed displacements of knots and other markings in km/sec. Plate XXXII represents the eruptive prominence of July 15, 1919, at three stages of the eruption, and Figure 9 is a pantograph sketch with velocity vectors. Figure 10 is a pantograph sketch of the "sigma" prominence of September 23, 1919, in six stages. In all these prominences it will be noted that the direction of motion of the knots is along the streamer into the chromosphere. In the first two cases a spot was the principal objective of motion, but in the last case no spot was present. This was also true of the "rocket" prominence of October 6, 1919.

Velocities of knots reduced directly from displacements observed in eruptive prominences require a correction for the motion of the prominence itself in order to reduce them to values relative to the sun's limb, i.e., the velocity of the prominence should be added to the vertical component of the knot as observed.

If this were done algebraically the equations would take the form:

$$\tan \theta' = \frac{V \sin \theta + V_p}{V \cos \theta}, \quad (4)$$

or

$$V' = \sqrt{V^2 \cos^2 \theta + (V \sin \theta + V_p)^2}, \quad (5)$$

$$V' = \frac{V \sin \theta + V_p}{\sin \theta'}, \quad (6)$$

where θ and V are observed position-angles and velocities, the θ' and V' are the corresponding corrected values, and V_p the velocity of the prominence at the time. Since there would be over three hundred of the transformations for the May 29, 1919, prominence alone, a graphical method was adopted.

An accurate cross-section sheet, 16×20 inches, ruled to 0.1-inch divisions was provided with a quadrant (of 10-inch radius graduated to degrees) in one corner. Two vector arms made of the same paper read the values of V and V' , and the value of V_p was laid off with dividers set for the velocity of the prominence. The values of the velocities given by the vectors as shown in the foregoing prominences are given in Table VII.

When data of this kind are studied, it will not be surprising that anomalous quantities should sometimes have to be dealt with.

From the list of measures, series of points located along a streamer were selected, and the distances from the center of attraction were measured by means of a scale bent along the streamer. The plot of these values

⁷ *Astrophysical Journal*, 50, 1919.



FIG. 7.—Internal motions of knots in the prominence of May 29, 1919, as measured at the stages shown in Plate XXX. The velocities at the numbered points are represented by the vectors.



TABLE VII

	Point No.	Meas. P.A.	Meas. V.	Corr. P.A.	Corr. V.		Point No.	Meas. P.A.	Meas. V.	Corr. P.A.	Corr. V.
		Degrees	km/sec.	Degrees	km/sec.			Degrees	km/sec.	Degrees	km/sec.
a. May 29, 1919. Fig. 7, stage (a). Prominence at rest at this stage.	1	275.0	6.5	.....	.....	c. May 29—Continued	21	350.4	18.4	.....	.....
	2	289.0	22.2	.....	.....		22	314.6	16.3	.....	.....
	3	14.9	55.5	.....	.....		23	312.5	14.5	.....	.....
	4	155.6	88.1	.....	.....		AB	271.2	24.5	273.2	9.8
	8	5.9	31.2	.....	.....	d. May 29, 1919. Fig. 8, stage (d). Prominence velocity, 27.9–60.0 km/sec.	1	301.3	68.1	2.9	36.0
	9	357.4	36.1	.....	.....		2	295.6	23.9	75.2	40.1
	10	3.1	22.3	.....	.....		3	295.5	62.5	8.4	27.3
	11	24.1	28.7	.....	.....		4	295.3	39.8	49.3	26.2
	12	22.2	50.8	.....	.....		18	343.1	18.0	.....	.....
	13	63.1	122.4	.....	.....		19	312.7	21.4	39.6	19.0
	14	63.5	130.6	.....	.....		20	312.4	51.1	344.5	36.0
	15	28.4	65.9	.....	.....		22	324.0	54.9	354.7	44.8
	16	5.8	59.6	.....	.....		A	306.1	26.3	24.0	16.8
	17	19.3	44.1	.....	.....		B	277.7	39.4	295.5	12.5
	18	152.4	83.2	.....	.....		C	340.2	55.3	10.2	53.0
	20	342.2	49.0	.....	.....	e. May 29, 1919. Fig. 8, stage (e). Prominence velocity, 60 km/sec.	2	267.4	44.9	102.6	15.4
	21	341.1	58.5	.....	.....		4	120.5	35.4	54.5	31.0
	22	51.2	91.1	.....	.....		5	346.4	43.5	49.7	65.8
	AB	170.5	11.9	.....	.....	a. July 15, 1919. Fig. 9, stage (a). Prominence velocity, 37.0 km/sec.	1	261.1	61.6	247.0	25.4
	BC	165.8	8.0	.....	.....		2	295.4	38.7	8.5	16.6
	BD	180.6	8.3	.....	.....		3	352.5	56.7	28.2	64.0
b. May 29, 1919. Fig. 7, stage (b). Prominence velocity, 5.5 km/sec.	1	22.8	53.8	.....	.....		4	5.4	53.3	38.6	68.0
	2	0.0	29.4	.....	.....		5	257.2	75.9	81.5	112.5
	3	340.7	6.1	.....	.....		6	39.2	91.9	53.0	119.0
	4	3.3	19.3	19.0	20.4		7	90.0	62.4	90.0	99.4
	5	152.9	109.1	150.4	111.6	b. July 15, 1919. Fig. 9, stage (b). Prominence velocity, 163.9 km/sec. No points were identifiable in stage (c).	AB	252.8	139.7	.....	.....
	6	44.9	86.2	47.3	90.5		2	271.5	63.5	89.2	100.0
	7	149.9	55.7	145.2	58.5		3	272.1	64.2	88.9	100.3
	8	137.8	22.6	129.1	26.6		4	322.2	50.0	73	138
	9	17.7	43.6	24.1	45.6		5	340.5	52.5	71	152.5
	10	22.7	13.1	40.9	16.0		6	47.6	148.8	69.5	291
	11	23.2	38.2	29.9	41.7		1	74.2	117.9	83.6	281
	12	22.9	34.8	30.6	37.4	a. September 23, 1919. Fig. 10, stage (a). The "sigma" prominence. Exposure at 4 ^h 55 ^m 40 ^s G.M.T.	1	293	53.7	.....	.....
	13	33.1	42.4	38.8	45.6		2	299	59.8	.....	.....
	14	25.9	42.5	32.0	45.2		3	293	44.6	.....	.....
	15	45.8	77.7	48.5	81.6		4	2	23.5	.....	.....
	16	54.8	91.5	56.7	96.1		5	285	49.2	.....	.....
	17	59.1	64.2	61.2	68.4		6	6	25.9	.....	.....
	18	64.2	132.9	65.0	137.9		11	279	70.1	.....	.....
c. May 29, 1919. Fig. 7, stage (c). Prominence velocity, 14.7 km/sec.	19	62.0	108.2	63.2	113.2	b. September 23, 1919. Fig. 10, stage (b). Exposure at 6 ^h 00 ^m 52 ^s .	1	193	64.4	.....	.....
	20	45.7	84.5	48.2	88.5		2	263	80.2	.....	.....
	21	25.2	155.4	.....	.....		3	279	60.3	.....	.....
	A	267.0	59.9	266.6	54.4		4	353	28.0	.....	.....
	B	264.5	102.8	264.3	97.4		5	32	61.8	.....	.....
	C	258.6	52.3	257.1	46.9		6	359	33.4	.....	.....
	D	258.6	84.7	257.6	79.0		7	218	95.3	.....	.....
	E	252.7	67.8	251.5	62.5	c. September 23, 1919. Fig. 10, stage (c). Exposure at 6 ^h 12 ^m 45 ^s G.M.T.	4	254	39.6	.....	.....
	F	252.6	75.6	251.5	70.4		6	4	46.5	.....	.....
	G	268.5	39.3	268.5	33.8		9	38	38.1	.....	.....
	H	268.5	99.0	268.5	93.5	d. September 23, 1919. Fig. 10, stage (d). Exposure at 6 ^h 34 ^m 07 ^s G.M.T.	6	314	67.1	.....	.....
	1	329.0	19.3	16.0	17.3		1	314	56.0	.....	.....
	2	295.1	23.5	326.5	11.9	e. September 23, 1919. Fig. 10, stage (e). Exposure at 6 ^h 46 ^m 20 ^s G.M.T.	6	296	64.0	.....	.....
	3	314.5	30.0	342.4	22.0		1	189	84.3	.....	.....
	4	334.6	34.0	0.2	30.9		2	268	73.2	.....	.....
	5	312.5	14.5	.....	.....		3	234	84.8	.....	.....
c. May 29, 1919. Fig. 7, stage (c). Prominence velocity, 14.7 km/sec.	6	306.9	17.6	3.5	10.5	f. September 23, 1919. Fig. 10, stage (f). Exposure at 7 ^h 09 ^m 05 ^s G.M.T.	4	279	63.3	.....	.....
	7	358.2	35.4	21.0	38.0		6	203	92.9	.....	.....
	8	357.7	23.3	30.7	27.1						
	9	6.3	35.4	28.0	40.0						
	10	37.7	76.4	45.3	86.2						
	11	89.8	106.9	90.0	121.6						
	12	304.1	19.1	354.5	10.8						
	13	303.5	26.7	332.7	16.6						
	14	298.8	19.2	347.2	9.5						
	15	269.8	8.6	90.0	6.1						
	16	276.5	11.6	66.9	3.7						
	17	320.2	26.3	354.2	20.4						

of the velocity, as ordinates, against the distance of the knot from the center of attraction, as abscissas, for the prominence of May 29, 1919, is given in Figure 11. The mean curve for each streamer was plotted, but only the mean of all the curves is shown here as a full line.

A study of this curve shows that the velocities increase, from about 25 km/sec. at 500,000 km above the chromosphere to about 200 km/sec. at the chromosphere, according to an exponential law which would give nearly constant velocities for points high up. One must, of course, take this curve to represent only the approximate general relation of velocities to distance, and not an exact statement of the conditions obtain-

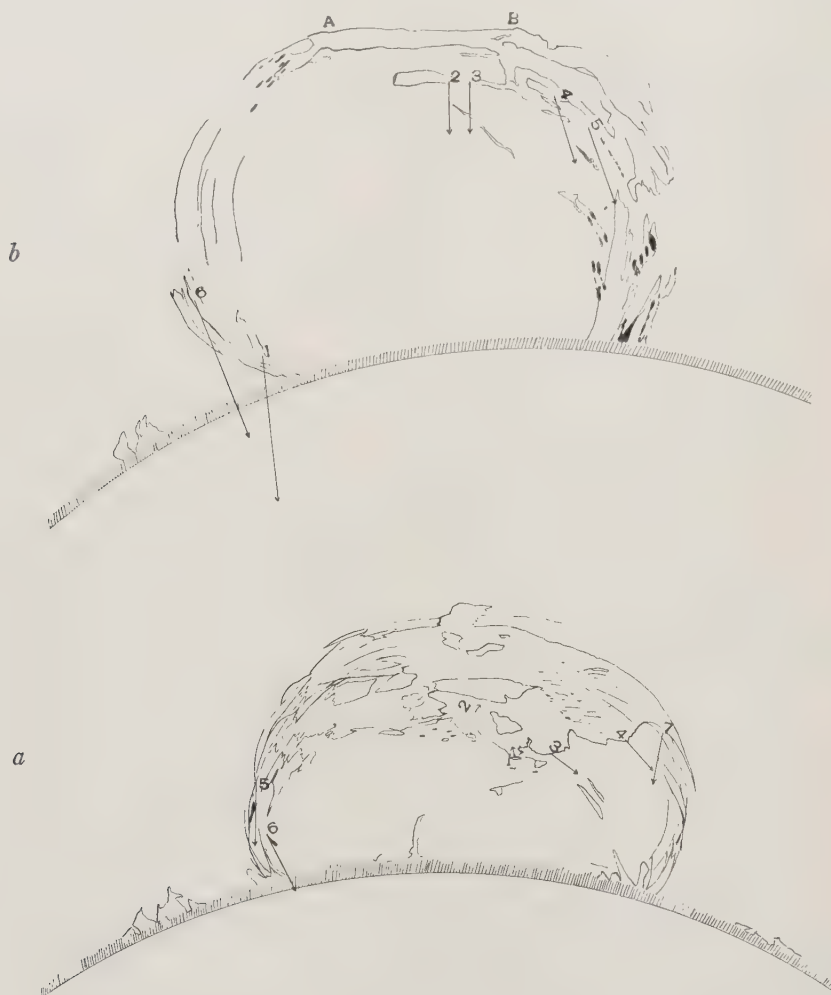


FIG. 9.—Internal motions of knots in the prominence of July 15, 1919, as measured at the stages shown in Plate XXXII, *a* and *b*. The velocities at the measured points are represented by the vectors.

ing at any point. Doubtless the velocity of a given knot is a function of its mass and other unknown physical quantities, as well as of its distance.

That gravity may or may not play a part in the descent of matter in the streamer may be determined by comparing the observed velocities with the values computed by the gravitational formula.

By way of anticipation one might suppose that the velocities observed would exceed those computed, since it is quite certain that the center of attraction, the spot, is exerting a force on the matter in the streamer which is the principal cause of the whole phenomenon. Curiously enough, however, this is not the case, as will be seen from Table VIII taken from plates where velocities near the chromosphere were measured.

The value at the chromosphere obtained from the mean curve (Fig. 11) is added by way of comparison. In Table VIII, s_1 represents the apparent origin of the streamer at the point where it appears to leave the main body of the prominence measured from the center of the sun, and s_0 is the observed distance of the

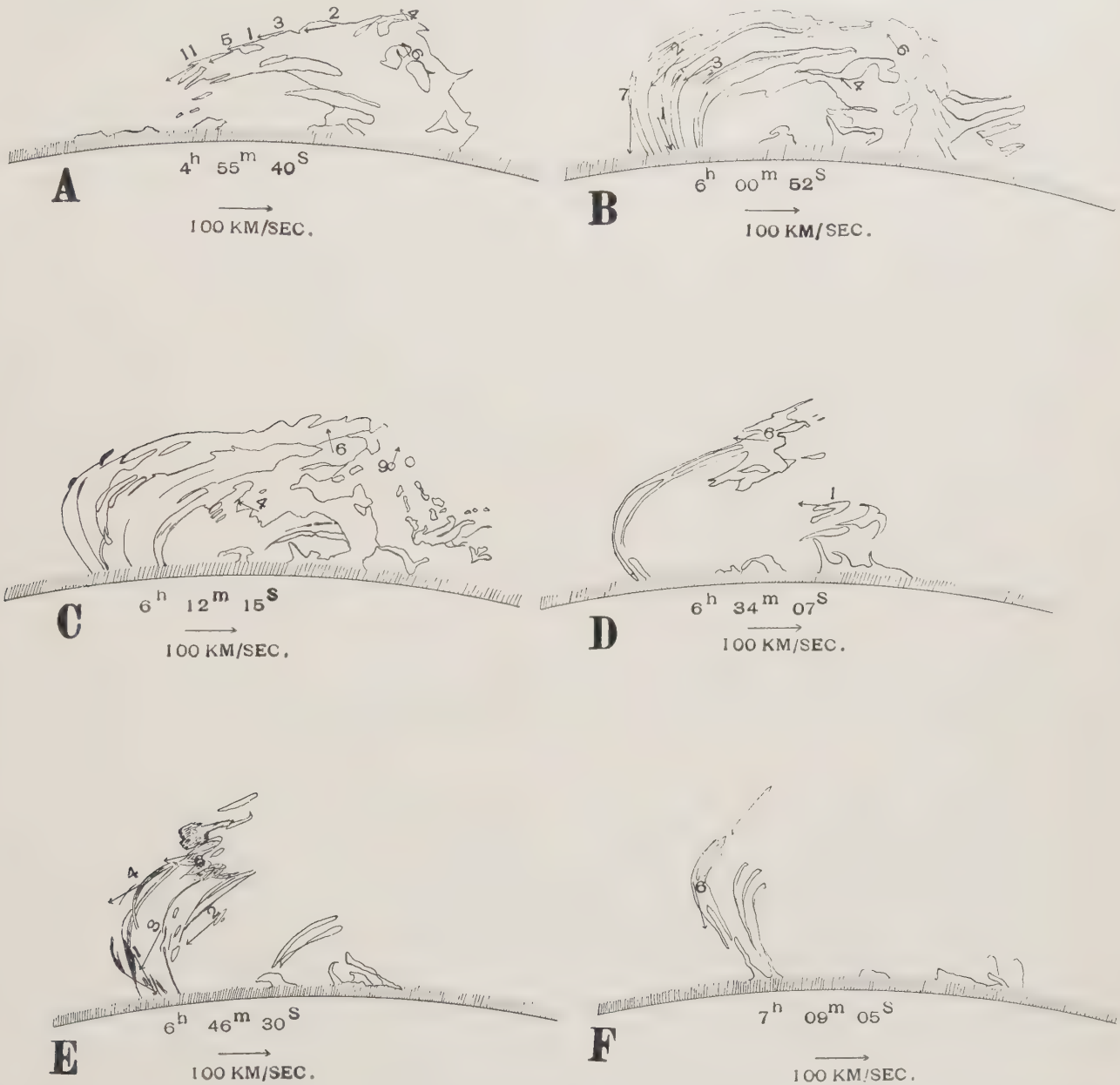


FIG. 10.—Lateral and internal motions of knots in the prominence of September 23, 1919, as measured at the corresponding stages shown in Plate XXVIII. The velocities at the numbered points are represented by the vectors.

knot from the center of the sun at the point where the velocity observed, $V_{\text{obs.}}$ was measured. $V_{\text{comp.}}$ is the velocity computed from the general gravitational formula

$$V_{\text{comp.}} = \sqrt{2gR^2 \frac{s_1 - s_0}{s_1 s_0}} + V_i \quad (7)$$

where V_i is the initial velocity. When V_i is put equal to zero, the formula becomes equation (1) on page 208. In equation (7), V_i was taken equal to zero except in the case of the mean curve, where it was taken to be 25 km/sec. $V_{\text{obs.}}$ is the vertical component of the measured velocity, since gravity acts in that direction

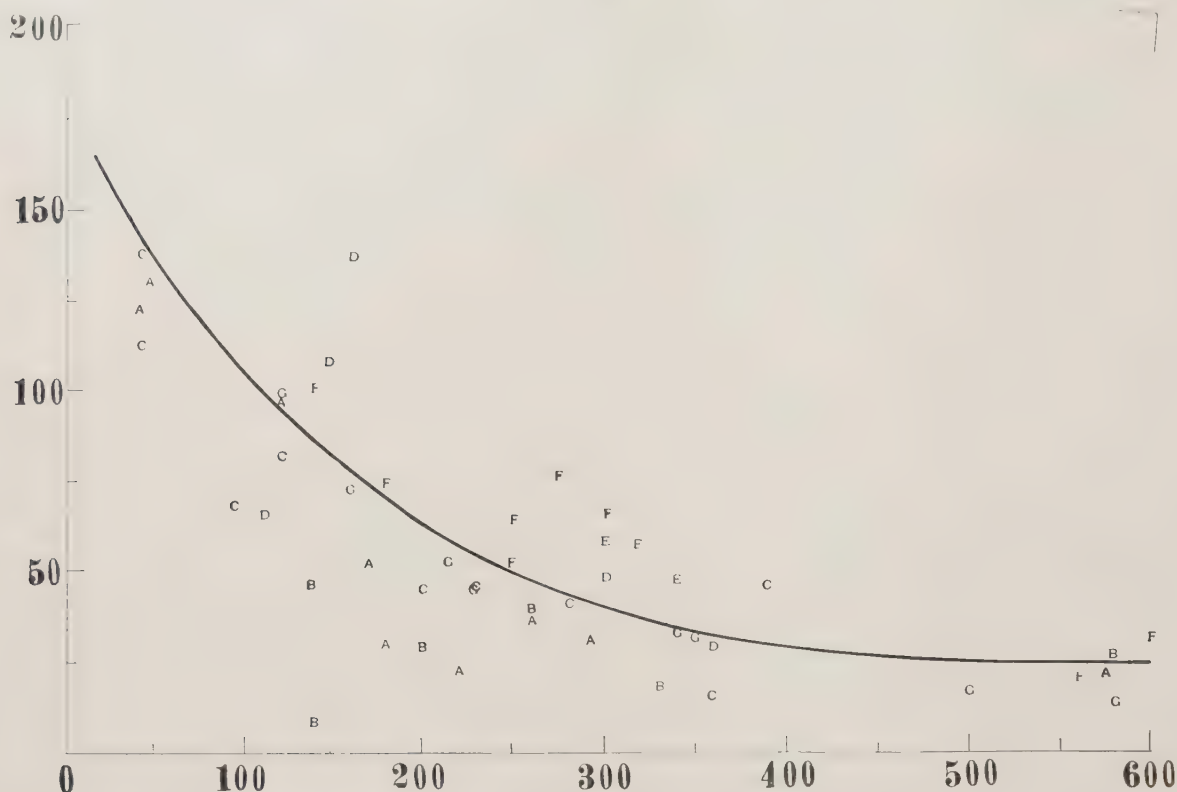


FIG. 11.—Plot of the motions of knots along the streamers in the prominence of May 29, 1919. The ordinates are velocities in km/sec., and the abscissas are distance from the center of attraction in thousand kilometers.

TABLE VIII

Plate No.	Knot No.	s_0	s_1	$V_{\text{comp.}}$	$V_{\text{obs.}}$	$\frac{V_{\text{obs.}}}{V_{\text{comp.}}}$
		km	km	km/sec.	km/sec.	
70.....	14	735,600	815,600	187	97	0.52
76.....	18	715,600	855,600	244	102	.41
78.....	12	755,600	865,600	210	86	.41
80.....	26	775,600	855,600	177	53	.30
81.....	18	775,600	855,600	177	63	.36
88.....	15	815,600	1,015,600	251	89	.35
89.....	19	815,600	1,035,600	261	94	.36
90.....	16	775,600	1,070,600	305	110	.36
91.....	2	755,600	1,075,600	321	63	.20
*.....		695,600	1,195,600	421	200	.5

* From the mean curve. V_0 taken equal to 25 km/sec.

and it is obtained by applying the coefficient $\cos(\theta - \phi - 180^\circ)$ to the measured velocity, where θ is the position-angle of the knot and ϕ is the position-angle of the vector of motion, the sign of the coefficient always being taken as positive.

Judging from the fact that the observed velocities are only from two-tenths to five-tenths of the values they ought to have from the gravitational component alone, and neglecting the attraction of the spot (which is the principal center of attraction in this case) altogether, one is led to question whether gravity has

anything to do with the motions of these knots. This view is further strengthened by data taken from the other eight prominences mentioned on page 223. These data are collected for comparison in Table IX.

TABLE IX

Prominence	Plate No.	Knot No.	s_0	s_z	$V_{\text{comp.}}$	$V_{\text{obs.}}$	$\frac{V_{\text{obs.}}}{V_{\text{comp.}}}$
			km	km	km/sec.	km/sec.	
July 15, 1919.....	26	2	765,600	945,600	255	79	0.31
July 15, 1919.....	29	1	735,600	1,015,600	313	102	0.32
September 23, 1919.....	Graph	.....	695,600	790,600	212	54	0.35
September 24, 1919.....	06	1	705,600	735,600	127	11	0.09
October 6, 1919.....	Graph	.....	695,600	782,600	204	95	0.47
March 27, 1920.....	59	4	695,600	735,600	147	25	0.17

It may be said, then, that in general these knots have velocities which are in the neighborhood of one-third or one-fourth of that which gravity alone ought to give to them.

MOTIONS IN THE PROMINENCES OF THE SPOT OR "SPLASH" TYPE

Particular interest is attached to prominences connected with the spots, in that they, without doubt, serve as indicators of the extended field of activity, which may have produced the spot itself.

Slocum⁸ has cited two cases of prominences near spots, in which accelerated motion of the matter into the spot was observed by him. Evershed,⁹ however, in writing about the Kodaikanal observations says, ". . . but we have never seen any evidence of the attraction of sun-spots for prominences," and again (*op. cit.*, p. 106), "No case has been found in which prominences were falling into sun-spots, but the reverse has several times been observed." His general conclusion (*ibid.*, p. 91) is that

The investigation has confirmed our previous belief that gas is always rising in the center of this type of prominence, and that this uprushing gas has a tendency to fall back upon the chromosphere at some distance from the sun-spot, sometimes building up banks or columns there (see Plate IX, Figs. 3 and 4), sometimes apparently continuing to rise and fall like fountains in the form of arches (Plate IX, Figs. 5 to 8), so that a fully developed spot-prominence covers a large space.

The plates referred to are not reproduced here.

A glance at Figures 7, 8, and 9 will convince one that the matter in the prominences of May 29 and July 15, 1919, was moving into the spot in each case connected with the prominence—and that in spite of the fact that the prominences were rushing upward, away from these spots, with high velocities, and that the spot in each case was of the round "normal" type. Plate XXXIII shows a direct photograph and a calcium spectroheliogram of the spots connected with the prominence of May 29, 1919.

In order to secure additional evidence, three prominences of the splash type and one of the fountain type were observed at short intervals and the motions measured in detail in the "blink" comparator.

The first of these, the splash prominence of August 17, 1917 (observed by Mrs. Pettit and myself), was connected with the great spot of that month. This spot was the largest and most active of the present cycle. Plate XXXIV shows a calcium spectroheliogram of both spot and prominence. Figure 12 is a pantograph sketch of this prominence. A streamer from the suspended wing is moving into the spot at the rate of 8 km/sec., and an isolated knot is descending with a velocity of 1 km/sec. The low, detached prominence under the wing is being projected into a point of attraction 250,000 km away at the rate of 7.4 km/sec.

The prominence of March 27, 1920, was connected with the great spot of that month. Plate XXXV shows this prominence and the associated spot. In this case 49 points were measured on a series of 21 exposures.

⁸ *Astrophysical Journal*, **36**, 265, 1912.

⁹ *Mem. Kod. Obs.*, **1**, Part II, 93.

Velocities into the spot seemed to average 30 km/sec. Two cases of repulsion were observed—one a streamer projected from the suspended cloud, and one an eruption from the same cloud. The first followed a flat trajectory and re-entered the chromosphere 150,000 km away. The eruption, on the other hand, rose nearly vertically with a uniform velocity of 25 km/sec. and faded away. This was followed with 6 exposures over a period of 15 minutes. The measures were made in the comparator.

The prominence of March 29, 1920, was also associated with this spot group. In this case 15 measures on 5 exposures were made. Two low splashes endured throughout the series. Three exposures were made on the high, separated splash. This prominence is shown in Plate XXXV. The first two splashes were moving into the spot with a slowly increasing velocity of 40 km/sec. and the high splash with a velocity of 10 km/sec.

The prominence of September 22, 1919, was an excellent case of the fountain type. On 15 exposures made at intervals of 5 minutes, 41 points were measured in the comparator. These measures indicate an average velocity of 35 km/sec. into the spot. One streamer was caught in the process of forming a closed loop of the fountain. This is the central streamer of the figure (Plate XXXVI) slightly inclined to the left. For half an hour, up to the seventh exposure, it had been standing motionless. On the eighth and succeeding exposures it is seen to descend, the whole column seeming to break away and follow it in its arched path.

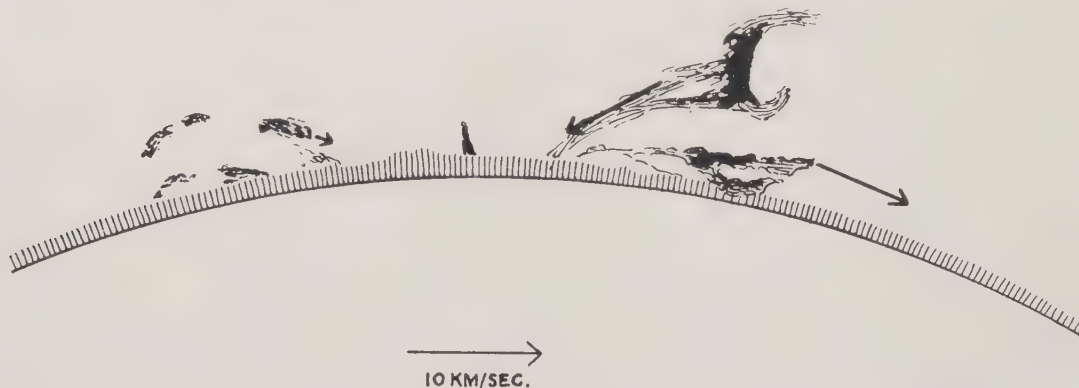


Fig. 12.—Lateral and internal motions of knots in the splash prominence of August 17, 1917, which was situated over the great spot of that month.

The velocity of the ascending end was 30 km/sec. The descending end had approximately the same velocity until about halfway down when the velocity increased to 80 km/sec. On the fourteenth exposure it touched the chromosphere and on the next exposure it had disappeared. Only 2 cases of repulsion were observed in this prominence out of the 41 measured points.

Slocum¹⁰ gives velocities of "16, 20, and 60 km per second" for three knots in his prominence of October 8, 1910, moving into a spot. These plates were remeasured in the comparator as previously described and the values 5.2, 8.0, and 44.3 km/sec. obtained. Two other knots at the left (*op. cit.*, Plate XI, 4^h34^m9), not mentioned by Slocum, were measured. Their distances from the spot as indicated by Slocum's arrow are 125,000 and 100,000 km, and their velocities 19.7 and 37.8 km/sec., respectively, toward the spot.

In his prominence of October 22, 1910 (*loc. cit.*), Slocum gives velocities of 80 and 110 km/sec. for two intervals between three exposures. All three knots in the streamer were measured in the comparator and I get for the first pair of exposures 18.4, 31.1, and 85.8 km/sec. in order of their increasing distances from the spot. For the small detached mass at the right I get 34.8 km/sec. Slocum gives 10,000 km/sec., which is obviously an error of printing.

Plotting these velocities against the distance of the knot from the spot, a nearly linear increase of velocity with the decrease of distance is obtained. The vertical component of the maximum velocity observed here was 52 km/sec. against 168 km/sec. computed by the gravitational formula, assuming the matter to have

¹⁰ *Astrophysical Journal*, 36, 265, 1912.

started from the point where the streamer leaves the prominence. Here, again, it seems that gravity can have little to do with the motion of the matter into the spot.

The prominence of May 9, 1911, was a splash over a small active spot on the southwest limb. Two exposures were taken by Slocum under good observing conditions and with an interval of 2 minutes (Plate XXXVII). I have measured the 4 small knots in the splash directly over the spot and 2 knots in the streamer at the left. The velocities obtained are given in Table X, all of which are directly toward the spot.

TABLE X

Point No.	Velocity	Point No.	Velocity
	km/sec.		km/sec.
1.....	38.4	4.....	54.9
2.....	69.6	5.....	21.3
3.....	31.1	6.....	21.3

Occasionally a brilliant spike will be projected from the vicinity of a spot, and, rising 20,000 or 30,000 kilometers, will fall again in the same region in a more or less circular arc. These are of the class of metallic prominences. One of these was observed on July 3, 1920, over an active spot on the west limb. It rose with a velocity of 30 km/sec., and, breaking into a spray at the highest point reached, precipitated itself on to the spot 25,000 km below. A broken stump remained as a brilliant spike, gradually fading during the next two hours.

In all the prominences here described and in any others which I have observed, no tendency for the prominence gases to pile up after falling back on the chromosphere was ever noted. On the contrary, they entirely disappear, like water poured into a pond. The prominences shown on Plates XXVIII-XXXII illustrate this. I cannot believe that "this uprushing gas has a tendency to fall back on the chromosphere at some distance from the spot, sometimes building up banks or columns there." In fact, I have shown a number of cases here where the matter was moving from the "banks" into the spot. I am convinced that this is the normal state of affairs, and that the "banks or columns" are of a more or less accidental nature—probably having risen through the coarser structure of the solar surface in the neighborhood of the spot—and are subject to the attractive forces emanating from the spot.

CENTERS OF ATTRACTION

That there are centers of attraction on the sun, where no spot or other marking appears, is to be inferred from the common circumstance of prominences from which streamers extend nearly parallel to the limb, finally turning downward and terminating in the chromosphere. The prominences of September 23, 1919, and October 6, 1919, already cited, were phenomena of this sort. Two such centers of attraction appeared under the prominence of May 29, 1919, at latitudes -10° and -25° (see pantograph sketch, Figures 7 and 8). Indeed, the streamers from the prominence descended to the former point, in preference to the spot, when the prominence had attained a height of 760,000 km.

Further evidence that the attraction is felt far out beyond the regions of the prominences is indicated by the effect of such a point which appeared on the western limb during the eclipse of June 8, 1918, at latitude 15° north, nearly midway between the "heliosaurus" and the neighboring prominence on the north, two prominences which attracted attention on account of their form. At the point where the streamers from the two prominences seem to converge into the chromosphere, the streamers of the corona radiate away in a striking fanlike form, strongly suggesting the "lines of force" about the pole of a magnet. On the photographs taken at Matheson, Colorado, these streamers can be traced at least a solar diameter from the center of attraction. The effect is nicely seen in the painting by Howard Russell Butler, from his visual observations, supplemented by a study of photographs of the eclipse.

That many of the cases of leaning prominences are due to such centers of attraction rather than to any atmospheric current, of the nature of a wind, in the corona may be inferred from the circumstances just

related. No stream effect of the kind one would expect, if winds in the corona actually produced these forms, has been found to exist. The case just cited, at the eclipse, certainly could not be so classified.

STUBBORN KNOTS AND EDDIES

A curious phenomenon was occasionally encountered in the measurement of the internal motions of prominences. Generally all the bright knots in a given region of a prominence were found to move with approximately the same speed and general direction. Occasionally one of these knots would remain stationary over several exposures, finally to be dragged along, rather reluctantly, with the rest of the matter which had been rushing past it at 20 or 30 km/sec.

In at least two cases these stubborn knots appear to have been the cause of an eddy in the prominence. In the prominence of May 29, 1919, these were first encountered near the points A and B in Figure 7c. Other points arranged themselves on either side of these, moving with low, slowly increasing velocities, in the reverse direction of the general stream toward the spot. A spiral arrangement then began to manifest itself, the free end of the prominence rotating like a corkscrew.

The linear velocities of 5 points on Plate XXXI were measured in the last exposures, and from these values, and the radius of the spiral, the period of rotation is given in Table XI.

TABLE XI

G.M.T.	<i>R</i>	<i>V</i>	<i>P</i>
	km	km/sec.	
7 ^h 19 ^m	90,000	40	3 ^h 56 ^m
7 57.....	110,000	32	6 00
8 23.....	140,000	37	6 35

The prominence of September 11, 1919, had the appearance of the quiescent type, in the forenoon. Toward afternoon a streamer extending out of one side indicated a strong attraction in that direction. Between 2^h 50^m and 3^h 20^m the whole prominence was torn apart, and it drifted off in the direction of the streamer with a mean velocity of 35 km/sec. Mean velocities of 50–60 km/sec. were maintained by knots at various times until the last exposure at 5^h 45^m.

A stubborn knot appeared at 3^h 45^m, and at 4^h 6^m it began a slow retrograde motion. An elliptical eddy formed, and in the next five minutes the matter on one side was moving in one direction with a velocity of 55 km/sec., and on the other side with an equal velocity in the other direction, while the matter at the two ends of the ellipse appeared to be stationary. The diameter of the eddy was 70,000 km, whence the period of rotation was 1^h 7^m.

A peculiar case was observed in the "rocket" prominence of October 6, 1919. This was the prominence from which a piece was torn away, and, following a circular trajectory, re-entered the chromosphere. A notch appears just under the point of this comet-like portion in the sixth exposure shown on Plate XXIX. It can be traced a little farther back into the tail each time in the succeeding exposures until the tenth one is reached. As a matter of fact, this notch is stationary and the prominence is moving over it in much the same manner that a rope would appear when dragged over a log. Here, then, we have an invisible stubborn knot, probably made of matter which does not radiate the H line of calcium.

STATISTICAL DATA ON ERUPTIVE PROMINENCES

1. *Velocities generated during an eruption.*—The twenty-four cases of eruptive prominences already given cover all the published data which I have been able to find, in which more than three observations were made during the rise of the prominence. It is obvious that where only two observations have been made the actual values of the velocities and heights are rather problematic, especially in the visual results. This applies more particularly to the more rapid motions.

The mean maximum velocity for the 24 cases is 153 km/sec. and a maximum velocity of 400 km/sec. was attained in 3 cases.

All cases of prominences reaching a height greater than 150,000 km were collected. Of the 25 cases found, not including any of the foregoing, the average velocity is 298 km/sec. This high average is due to several individual, high velocities. Buss observed one on March 3, 1907, which reached a height of 750,000 km with a velocity of 600 km/sec. I have been unable to learn the details of the observation. Trouvelot observed one on July 11, 1892, which reached a height of 427,000 km with a velocity of 715 km/sec. Lockyer observed velocities of 300–400 km/sec. Secchi states that “Respighi declares he has observed ‘initial’ velocities of 600, 700 and even 800 km/sec.,” but that “these figures are in need of confirmation.” If this means that the “initial” velocities were reduced from the observed velocities with the gravitational theory, then the values are erroneous in the light of what we have seen to be the character of the motion of eruptive prominences.

Fényi observed an eruption on June 17, 1891, in which a radial velocity of 800 km/sec. was measured and a velocity of ascent of 485 km/sec. observed. The circumstances of the observation, however, were not the best. The whole ascent only lasted about 210 seconds, during which he observed 7 transits of both apex and base, determined the line-of-sight velocity with the micrometer, and observed the character of the spectrum. The duration was computed from the times of transit, allowing suitable time for resetting the telescope and making the record. An error in this estimate, of course, would affect the result abnormally on account of the short duration.

Proctor is often quoted for a velocity of 800 km/sec., but this was an initial velocity computed from Young’s observation at Sherman, Wyoming, on September 7, 1871, when a velocity of 217 km/sec. was observed. The computation was based on the gravitational theory and a hypothetical atmospheric resistance.

All these observations were made visually, with rather short intervals and two observations of the time, and consequently they are subject to a large percentage of error.

Line-of-sight velocities as high as 1000 km/sec. have been reported several times. The interpretation of these results is somewhat doubtful as yet. Generally no two lines of the same element will give even approximately equal velocities, and other elements show no shifts at all. Young’s observation of August 3, 1872, illustrates this point.

We may conclude, then, that velocities greater than 400 km/sec. occur only rarely, and the results cited above must be accepted with caution until confirmed by photography.

2. *Positions of the breaks in the curves.*—There seems to be no general connection among the breaks in the curves. Thus in the prominence of May 29, 1919, there were 4 breaks in 760,000 km, while in that of July 15, 1919, there is only 1 break in 720,000 km. This circumstance would preclude the theory of a stratified atmosphere, as an explanation of the sudden increases in velocity, unless one may suppose that the stratification varies in an erratic manner.

3. *The distribution in latitude.*—This shows a strong maximum in the sun-spot zones, although some have been observed in high latitudes. Deslandres’ prominence of May 31, 1894, appeared in latitude 80°. Those observed in the past ten years appeared almost entirely in the hemisphere 0°–190° of longitude, while those observed prior to that interval regress into the other hemisphere.

4. *Relation of the velocity to height.*—Generally speaking, the higher prominences have the higher velocities, as one might expect to result from the principle of motion found to obtain. There are, on the other hand, numerous instances of high velocities at low altitudes. Buss observed a velocity of 280 km/sec. in a prominence which reached a height of only 30,000 km. At this point the normal velocity is only 5 or 10 km/sec.

5. *Relation between spots and eruptive prominences.*—That there is, in general, no apparent connection between spots and prominences has been shown by Lee.¹¹ This applies to eruptive prominences in particular. While the eruptive prominences of May 29 and July 15, 1919, were associated with sun-spots, yet in this respect they were quite in a class by themselves. No other eruption observed with a spectroheliograph shows any connection between a spot and an eruptive prominence, and generally no marking appears on the disk-plate in the region of the eruption.

¹¹ *Astrophysical Journal*, 45, 206, 1917.

While the evidence of the visual observers is not of such a certain nature, and occasionally no mention is made of the condition of the disk in the region of the eruption, the same general rule applies here, that the connection between sun-spots and eruptive prominences is of a purely accidental nature. Indeed, one would suppose that the presence of the spot would hinder rather than excite the eruption, judging by the rapid descent of the matter into the spot in the two cases cited.

6. *No change in form or in any other respect* can certainly be distinguished in the prominence at the time when the sudden change in velocity (the "impulse") occurs. This, of course, is based on a study of the spectroheliographic plates and the prints available to me, and is not complete. The visual observations contribute nothing to studies of this kind. Altogether no safe conclusion can be drawn on this point from the material covered in this investigation.

SUMMARY OF THE PRINCIPAL OBSERVATIONAL EVIDENCE

1. Prominences of the splash type are always connected with sun-spots, and consist of one or two wings on either side of the spot with projecting spikes radiating away from it, many of them broken and describing curves similar to the "lines of force" about a magnet. Normally the matter about the spot is moving into it with accelerated velocities averaging about 35 km/sec., sometimes reaching 100 km/sec. Occasionally a streamer may be projected from one of the wings away from the spot, or a spike rise from the region of the spot, with similar velocities. This is not the normal condition, however. The distribution of these objects observed in the last twelve years shows a sharp maximum in longitude 145° .

2. Tornado prominences are found to be twisted in one direction only, such that the direction of rotation is interpreted to be in the clockwise direction in both hemispheres.

3. Eruptive prominences have been shown to move with uniform velocity, suddenly accelerated at intervals as if by an impulse. This conclusion is substantiated by both visual and photographic observations in every case where sufficient data are obtainable to determine the character of the motion.

4. There is some evidence of secondary eruptions and possible decrease of velocity at the end of an eruption, but the latter is based on only a few visual observations.

5. Fading at the end of the eruption is very rapid, sometimes obliterating the whole prominence in a few minutes, and sometimes only partially.

6. The maximum velocity observed in the best-determined cases reaches 400 km/sec. Velocities greater than this are to be accepted with less confidence.

7. Streamers and knots in prominences show velocities toward the sun's surface of about one-third that which gravity alone would give to them.

8. There is no evidence of the piling up of matter which is torn from a prominence, or ejected from the region of a spot, and which returns to the chromosphere.

9. Stubborn knots are found which sometimes appear to produce eddies in portions of a prominence where there is a streaming of matter.

10. There seems to be no connection between eruptive prominences and spots, other than of an accidental nature.

11. There is no apparent relation between the breaks in the curves and the heights which they indicate.

THE PROBABLE NATURE OF ERUPTIVE PROMINENCES

That we have to deal with real motions of bodies of gaseous matter and not with a "transference of luminescence," as Brester imagined, is difficult to prove, as no crucial test has yet been devised to settle the question, but the motions of the knots and streamers are such as to give a strong impression of the actual transference of matter. The delicate detail of a prominence, which, in its more general structure, often undergoes only a slow change while the whole body is moving with a velocity of 200 km/sec., can hardly be compared to the aurora as an example of the "transference of luminescence."

If we accept this view of the matter, the question now arises as to the origin of the eruptive forces which produce these high velocities. Young's idea, which was accepted as the best available by many of

his contemporaries, may be briefly summarized as follows. The photosphere consists of the condensed cloud surface, of which the granules are the upper ends of columns of condensed vapors, between which rise the heated currents from within, and in their passage through these "quasi-pipes" they may encounter contracted passages which may result in explosions giving rise to motions "which must have exceeded 200 miles per second" in the prominence of September 7, 1871.

Secchi was inclined to attribute a great part of the velocity to an extreme difference of density between the prominences and the atmosphere in which they rise.

Both of these views of the mechanics of an eruption of a prominence are untenable for cases of quiescent prominences which later become eruptive. The prominence of May 29, 1919, was a case of this kind.¹² Young's view would necessarily admit a complicated spectrum, which is not generally the case, for the spectrum is often as simple as that of the quiescent prominences. Secchi's view would reverse what seem to be the relative densities of the prominences and the corona. Secchi was under the impression that the hydrogen spectrum is present in the inner corona, which is now believed not to be the case.

Arrhenius and others have attempted to use radiation pressure to explain comets' tails, prominences, and the corona. Fitzgerald first suggested that the light-pressure on gases is equal to the pressure exerted on a black body of equivalent cross-section multiplied by the coefficient of absorption of the gas. Lebedew tested this theory experimentally and showed that the relationship stated by Fitzgerald is correct within 30 per cent of the predicted value, which was the limit of accuracy attainable by the method he used. His conclusion¹³ was, however: "These experiments refer to masses of gas under atmospheric pressure, and the numerical values found cannot be directly applied to the excessively rare gases of comets' tails." The coefficients which he found were of the order of less than 0.01.

That there is a certain dimension for which the light-pressure is a maximum per unit area on a small spherical body was first pointed out by Schwarzschild. He showed that, from considerations based on the electromagnetic theory of light, the pressure is a maximum per unit area, when the circumference of the sphere is about equal to the wave-length of the radiation incident on it. The pressure is then over twice the value given by the energy formula. As the diameter diminishes, the pressure falls off in an exponential manner on account of diffraction effects, and is rapidly reduced to zero.

The appearance of Halley's comet brought forth a number of papers on the subject. Nicholson¹⁴ gives a shorter method of reducing the equations, and Proudman,¹⁵ a still shorter method. Debye¹⁶ discusses light-pressure on small spherical particles and molecules of various hypothetical constructions. In all these, the equations lead to the determination of the quantity $P/\pi a^2 E$, which is the ratio of the pressure computed by the electromagnetic theory to the pressure computed by the simple assumption that the energy received per unit volume of the incident beam is all converted into a repulsive force. Curves giving this ratio in ordinate against the argument $2\pi a/\lambda$ (the circumference in terms of the wave-length) are given by the authorities quoted above.

On the assumption that the molecule is a small spherical absorbing body we may compute the radiation pressure from the formulae mentioned above. We will follow Nicholson. He gives (*loc. cit.*):

$$\frac{P}{\pi a^2 E} = S_2 + \eta + \zeta \quad (8)$$

$$S_2 = \frac{2}{k^2 a^2} \sum_1^\infty \frac{2n+1}{n(n+1)} \frac{1}{1+T_n^2} \quad (9)$$

$$\eta = \frac{2}{k^2 a^2} \sum_1^\infty \frac{n(n+2)}{(n+1)} \frac{1}{R_n R_{n+1}} \quad (10)$$

$$\zeta = \frac{2}{k^2 a^2} \sum_1^\infty \frac{n(n+2)}{n+1} \left[\frac{(n+1)^2}{k^2 a^2} - 1 \right] \sigma_n \quad (11)$$

¹² *Astrophysical Journal*, 50, 207, 1919.

¹³ *Ibid.*, 31, 393, 1910.

¹⁴ *Monthly Notices*, 70, 544, 1910.

¹⁵ *Ibid.*, 73, 535, 1913.

¹⁶ *Annalen der Physik*, 30, 57, 1909.

The diameters of molecules of various gases have been determined by a number of methods in recent years. The values obtained are of the order $2 \cdot 10^{-8}$ cm. For hydrogen the mean value is about $1.12 \cdot 10^{-8}$ cm. This gives, then, $a = 0.56 \cdot 10^{-8}$ cm, and taking λ at $5.5 \cdot 10^{-5}$ cm for the effective wave-length of radiation we have

$$Z = \frac{2\pi a}{\lambda} = 0.001274, \quad R_{-1} = 1, \quad R_0 = 1, \quad R_1 = 6.16 \cdot 10^{-5}, \quad R_2 = 3.4 \cdot 10^{12}.$$

From these values it is readily seen that only the value $n=1$ need be taken in the summation. Then, from these values:

$$\begin{aligned} \sigma_1 &= 7.7 \cdot 10^{-25} \\ S_2 &= 79 \cdot 10^{-13} \\ \eta &= 8.8 \cdot 10^{-13} \\ \zeta &= 35 \cdot 10^{-13} \\ \frac{P}{\pi a^2 E} &= 12.3 \cdot 10^{-12} \end{aligned} \tag{12}$$

A simple check formula $\frac{P}{\pi a^2 E} = \frac{14Z^4}{3}$ may be applied here, and the value of Z being so near the origin the check ought to hold with considerable accuracy. From this formula we get:

$$\frac{P}{\pi a^2 E} = 12.3 \cdot 10^{-12}.$$

Let us now consider the pressure on a molecule of hydrogen near the chromosphere. For all practical purposes we may consider the radiating surface to be a plane of infinite extent.

In Figure 13 let m represent the molecule from which the perpendicular h is dropped to the radiating surface. Let the energy of radiation per unit area from the small elementary area $r \, dr \, d\theta$, falling on m , be E . The pressure P then varies directly with E , inversely with the square of the distance $\sqrt{h^2 + r^2}$, and directly with the cross-section of the beam $r \, dr \, d\theta \frac{h}{\sqrt{h^2 + r^2}}$. The component parallel to h is the energy so obtained, multiplied by $\cos \phi = \frac{h}{\sqrt{h^2 + r^2}}$. The sum of the differential components is

$$\int_{r=0}^{r=\infty} \int_{\theta=0}^{\theta=2\pi} E \frac{h^2 r \, dr \, d\theta}{(h^2 + r^2)^2} \tag{13}$$

Integrating this, we get for the energy delivered to m , effective outward along a solar radius,

$$E' = \pi E, \tag{14}$$

and the consequent pressure for a perfectly absorbing molecule is

$$P = 12.3 \cdot 10^{-12} \pi^2 a^2 E. \tag{15}$$

Taking the solar constant at 2 cal./min. = $1.4 \cdot 10^6$ ergs/sec. for the earth's distance, its value at the sun's surface will be forty-six thousand times as great, and the energy per cu. cm effective as pressure is

$$P = 12.3 \cdot 10^{-12} \pi^2 a^2 E \frac{1}{V} = 79.2 \cdot 10^{-28} \text{ dynes},$$

where V is the velocity of light = $3 \cdot 10^{10}$ cm/sec.

Now the mass of a hydrogen molecule is given by Millikan as $1.66 \cdot 10^{-24}$ gm. Taking $G = 27.6$ g we get for the ratio of the attraction of gravity Gm , to the light-pressure P , at the sun's surface, $Gm/P = 5.7 \cdot 10^3$, i.e., gravitational attraction on a hydrogen molecule exceeds light-pressure some half-billion times, assuming the molecule to be a perfectly rigid absorbing sphere.

We cannot, of course, admit the rigid molecule as a final argument in the light of what is known to be the probable constitution of it. That "resonant pressure," due to the electrons circulating in orbits having periods approximating that of the incident radiation, probably exists, cannot be doubted. Page¹⁷ computed the value of such a resonant pressure on molecules of sodium vapor. For resonant frequency at 9000 Å the value of the pressure is a maximum, and exceeds gravitation "thirty times or more." While the derivation of this result is based on the doubtful assumption that the resonant effect is applicable for the integrated spectrum, we may accept the result and show that it does not apply to the prominences near to the chromosphere.

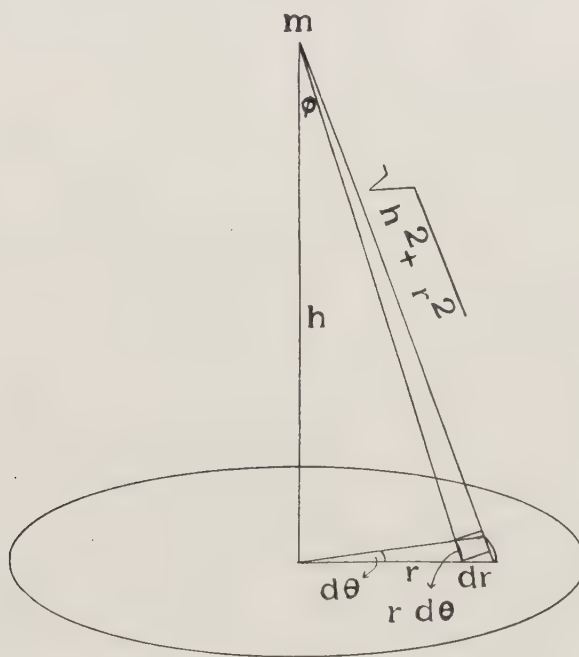


Fig. 13

In his equation for the energy received, $1/c$, he presumes radiation from a full hemisphere of the sun. For a prominence at the chromosphere, the area of the exposed radiating surface is very small and the rays are nearly all inclined at an angle, while the law of gravitation remains unchanged.

Possibly the more reasonable assumption is that the energy producing the pressure must be some part of that absorbed by the gas. Poynting¹⁸ discusses this and arrives at the conclusion that "no gas can be repelled."

Eddington,¹⁹ in discussing the envelopes of comet Morehouse, concluded that the velocities of the ejected particles were hundreds of times greater than those produced by gravity. Light-pressure could not account for it.

That radiation pressure does not furnish the motive power for eruptive prominences is apparent from several considerations.

1. If the radiation pressure on a molecule exceeded gravity at the sun's surface the chromosphere could not exist, neither would the quiescent prominences.

¹⁷ *Astrophysical Journal*, 51, 65, 1920.

¹⁸ *The Pressure of Light*, p. 92.

¹⁹ *Monthly Notices*, 60, 442, 1910.

2. The velocities of the eruptive prominences would all be nearly the same at the same height, or at least there should be a tendency in that direction. This has been shown not to be the case.

3. Radiation pressure acts radially. Some eruptions have taken place at considerable angles to the radius. In the case of the prominence of September 8, 1919, this angle was nearly 57° and the prominence traversed this path in a nearly straight line a distance of 480,000 km.

4. If radiation pressure produced the observed motions, they would be continuously accelerated rather than uniform.

Whatever the nature of the expelling force, several properties are apparent from the observational evidence presented here.

1. The force is very probably of the same nature for all eruptive prominences, since the law of motion appears to be a general one.

2. The force acts at a distance. The quiescent prominences which become eruptive are almost detached masses connected to the sun by streamers. These are well represented in the prominence of May 29, 1919. In these streamers the matter is moving into the sun, hence the force of the eruption cannot be traveling outward along them unless it be of an electrical nature.

3. Further evidence that the force acts at a distance and also over short periods of time is obtained from the sudden increases in velocity of ascent after the prominence is entirely free from the sun.

4. It must follow the law of motion shown here to be a generalization.

5. It generally produces no visible disturbance on the photosphere.

6. It must be capable of acting between individual molecules of a gas and the sun.

7. It must produce the high velocities observed.

8. It must act at times at a considerable angle to the vertical.

9. The value of the eruptive force probably varies over a considerable range.

The character of the motion here presents peculiar difficulties, if we are to accept the precepts of Newtonian mechanics. Uniform motion in a straight line subject to sudden increases is not to be expected in a gravitational field. We must account for uniform motion observed over a space greater than a solar radius, enduring for several hours at least, and we have no reason to believe that these are limits in any sense.

Before pursuing the matter farther we are in need of two pieces of evidence quite lacking, viz., the densities of the prominences and of the coronal atmosphere. From appearances one would judge that the densities are very low, and, if anything, that the coronal density is the less. If we assume a density of 1 atmosphere in the chromosphere, the density in the region of the ordinary prominences is less than the best vacuum we can produce, on account of the value of superficial gravitation there.

Some facts bearing on the coronal density and its relation to the densities of the prominences may be stated here. The high velocities of the eruptive prominences would make a coronal density much short of a good vacuum seem impossible. That the prominences could preserve any kind of form while moving at the rate of 100 km/sec. through an atmosphere of density comparable with its own is quite inconceivable.

One point of observation must not escape attention, however. In many cases the matter of the prominence is broken up, apparently, and scattered all along the path traversed, as was the case of Young's prominence of September 7, 1871, and also of the prominence of September 8, 1919. There is some tendency to expand in the direction of motion in nearly all cases, but there are some exceptions. The prominence of July 15, 1919, is a good example.

This expansion, and even torn structure, may be assigned to other causes than movement through a resisting medium, and the effect of such a medium would be to produce a strongly negatively accelerated motion.

Another fact of observation may be taken from the deflection of starlight through the corona. If such a deflection were produced it would cause the star to shift its position away from the limb of the sun in the same manner as Einstein's theory predicts. The plates taken by Eddington and Cottingham at Principe, and by Crommelin and Davidson at Sobral on May 29, 1919, show such shifts, uniformly greater than Einstein's theory predicts, with the exception of 2 cases out of 7.

The mean line which Dyson²⁰ adopts, in the discussion of the measures, gives a difference of 0".12 for a distance of a radius from the limb. This outstanding excess or a part of it, if real, may be interpreted as refraction, if Einstein's theoretical value of the shift be accepted. Even if this result could be confirmed, we would be at loss for a means of making an application of it, since the properties of the coronal gases and the law of refraction obtaining there are unknown.

Some evidence may be taken from the passage of comets through the corona. Several remarkable cases are on record, as may be seen from the following table:

TABLE XII

Comet	Distance from Sun's Surface at Perihelion	Comet	Distance from Sun's Surface at Perihelion
	km		km
1680.....	231,300	1882 III....	530,300
1843 I.....	126,700	1887 I.....	111,700
1880 I.....	186,500		

All these distances are less than the maximum observed height of eruptive prominences.

Observers of these comets could detect no physical changes which might be attributed to passage through the corona. The comet of 1882 split up, it is true, the nucleus dividing into a number of parts and a portion of the body becoming two separate attendants, but the phenomenon occurred on October 3, sixteen days after passage through the corona. The brilliancy of the comet was so great that it was observed almost without interruption throughout this period. From this we must conclude that the coronal atmosphere has no observable effect on the matter in the region of the nucleus of a comet, when the latter is moving through it at the rate of 500 km/sec.

Altogether the evidence points to a very low density, but further than that it does not tell us much.

Observational material on the densities of the prominences is quite lacking. About our only hope of securing such data seems to be from a study of the widths of the lines of the spectrum of the prominence by means of the spectro-interferometer. This would require a study in the laboratory of the effect of pressure on the width of lines in the spectrum of gases occurring in the prominences, and a study of the electrical and temperature effects. These lines would then be observed in the spectrum of prominences by means of a spectro-interferometer especially designed for the purpose. The pressures would then be obtained from curves determined in the laboratory. I hope to find means of carrying out studies of this kind.

Let us suppose that the coronal atmosphere is negligible so far as the prominences are concerned. Since the force cannot act continuously, let us suppose that the prominence is projected into space by a sort of explosive force acting for a short time. In order to produce uniform motion it will be necessary to neutralize the force-vectors on the prominence in some way. About the only forces opposing gravity in the region surrounding the sun, with which we are at all familiar, are light-pressure, electrostatic repulsion, and possible corpuscular bombardment. The inadequacy of light-pressure has already been shown. Let us see, then, what may be the character of an eruption generated by electrostatic repulsion.

If we accept the theory of Young that the photosphere is a surface of cloud, we may assign to it the properties of an electrical conductor. The amount of the positive charge which it may carry, due to the ejection of negative electrons, is difficult to estimate. This charge depends on the molecular agitation, short-wave radiation, and possible radium content of the sun. All things considered, the process of partition of the negatively charged electrons will go on until the forces ejecting them are balanced by the residual positive charge. However, the speed of ejection is so high, 17,000–150,000 km/sec., that for all practical purposes large numbers must escape the vicinity of the sun, leaving the photosphere essentially a positively charged sphere with respect to surrounding space.

²⁰ *Philosophical Transactions of the Royal Society* (London), 220, 332, 1920.

Suppose, then, that the seat of the eruption lay on the sphere. The repulsive forces acting on the molecule of gas in a prominence would be given by²¹

$$F = \frac{Ee}{f^2} - \frac{e^2 a^2 (2f^2 - a^2)}{f^3 (f^2 - a^2)^2} \quad (16)$$

where

E = the charge on the sun
 a = the radius of the sun
 e = the charge on the molecule of the prominence
 f = the distance of the molecule from the sun's center

If we let $d = f - a$ = the distance of the molecule from the sun's surface, then we have approximately

$$F = \frac{Ee}{a^2} - \frac{e^2}{4d^2} \quad (17)$$

when $\frac{f-a}{a}$ is small, i.e., the molecule is near the surface of the sun. From this we see that F is negative, i.e., that the force is attractive, unless

$$E > \frac{ea^2}{4d^2}. \quad (18)$$

This phenomenon is familiar to every experimenter. A pith ball is first attracted to a charged body by the induced charge on the near side. The ball will remain in contact with the charged body until separated a small distance, when it will fly away, repelled by the charge of contact. Since d is the only variable in the foregoing inequality, then there is a critical value for d for which

$$E = \frac{ea^2}{4d^2}. \quad (19)$$

At this distance the charged molecule will be suspended in unstable equilibrium. Beyond this point it will be repelled continuously, while for smaller values of d it will be attracted continuously toward the sun.

In the particular case of the sun, however, or in any sphere of considerable mass, the foregoing equation must be modified by inserting the gravitational vector. As applied to the sun, this equation of critical distance becomes

$$E = \frac{a^2}{e} \left[\frac{e^2}{4d^2} + mg \frac{a^2}{(a+d)^2} \right] \quad (20)$$

where m is the mass of the molecule and g is the value of superficial gravitation.

If we neglect other circumstances, then the value of d determined by this equation should be the height to which the most stable prominences rise and remain free from the chromosphere. If the sun's potential and that of all the prominences were constant, d would also be constant, but this is hardly to be expected, especially of e . For any particular prominence this leads directly to a relation between E and e .

A remarkable case of this sort was the prominence of October 13, 1919. This had the form of a detached arch, most of the material being concentrated near the crest. It remained unchanged, except in minor details, during seven and one-half hours of continuous observation, including 40 exposures and a number of visual observations. In this case $d = 120,000$ km, and putting the atomic mass of calcium at $66 \cdot 10^{-24}$ gm we have

$$Ee - 21.5e^2 = 62.7 \cdot 10^{-15}. \quad (21)$$

²¹ J. J. Thomson, *Elements of Electricity and Magnetism*, p. 156.

Several facts are apparent from equation (20). First, that electrostatic repulsion cannot ordinarily produce an ejection of matter without an additional starting force. Second, that the matter ejected can be in equilibrium only at one point—where d has the critical value. Hence, uniform motion cannot exist under these circumstances alone. Earnshaw²² has proved the general theorem that an electrified body cannot be in stable equilibrium in an electric field under electric forces alone.

The electrical status of eruptive prominences is further embarrassed by the fact that there is no certain case on record where magnetic disturbances can be associated with the occurrence of an eruption, such as is often found in the appearance of a great spot. The outcome of the attempts to detect the Stark effect in the sun is awaited with interest.

Deslandres and Crookes have proposed the hypothesis of a cathode-ray bombardment to explain comets' tails and prominences. The high velocities of the cathode particles would make the force of repulsion follow the inverse square law from the origin of the particles on the sun's surface. This must be a purely local phenomenon or we should expect eruptive prominences to be the normal condition rather than the converse. We are, then, confronted again with an acceleration which does not agree with observation.

CONCLUSION

Such a simple law of motion, as has been found to obtain, cannot be expected to result from a complex relation of forces in every case, but, on the other hand, we should look for a simple condition to exist. I have shown that, in general, streamers and knots moving into spots and areas of attraction are subject to accelerated motion just as we might expect them to be, when attracted by a local force; and that the vertical component of velocity is only about one-third that which it would have under gravity alone, neglecting the force which is apparently causing the motion.

This suggests what is probably the simplest explanation of all, namely, that the gravitational attraction of the sun for the matter in the prominence is so modified as to have practically no effect. Whether this is due to loss of gravitational properties, or to a suspension by means at present unknown, is difficult to decide. It is evident, however, that the prominence is still under the influence of the magnetic and possible electric forces on the sun, as is indicated by the downpouring streamers, which send matter into the spots and areas of attraction in spite of the high velocity of the eruptive prominence itself.

There is also, often, some lateral motion of the prominence toward the principal point of attraction, as is shown by the movement of the prominence of May 29, 1919, of about 8° of latitude toward the spot. Evershed records a movement of 5° of latitude toward the area of attraction in the prominence of May 26, 1916.

The expulsion of the prominence and the changes in its velocity are probably due to a periodic force, acting for a short interval and with a violence which increases continuously. The evidence on this point is contained in Table XIII, in which are tabulated all the eruptive prominences which show more than one impulse. Of the nine cases, six show continuously increasing values of the change of velocity (ΔV) due to the impulse. The last three show slightly decreasing values.

Since the prominence is moving with uniform motion, ΔV is proportional to the force applied, and the time during which it acts, if the mass remains constant. If the repelling force is one which varies with the reciprocal of the distance or a power of this greater than unity, then for every case in Table XIII the force is always increasing at successive impulses.

Nearly any periodic force capable of repelling gas molecules would satisfy these conditions. Probably the periodic ejection of showers of electrons from a disturbed area in the photosphere would satisfy the conditions. The high velocities of these bodies would cause them to yield their energy to a number of gaseous atoms before they were brought to rest by attaching themselves to one of the atoms higher up in the prominence, thus distributing the repulsive force throughout its mass. The speed (17,000–150,000 km/sec.) would permit an electron to move from the bottom to the top of any prominence in a few seconds.

²² Clerk Maxwell, *Electricity and Magnetism*, 1, 174.

This ability to distribute its energy throughout the prominence might explain the fact that no certain changes of form of the prominence can be attributed to an impulse occurring between two exposures with the spectroheliograph. On the other hand, the velocities given to calcium atoms would, on the average, be much less than those attained by hydrogen. This might explain the more elongated, columnar form of some promi-

TABLE XIII

Plot No.	Prominence	Height in 1000 km	V	ΔV
			km/sec.	km/sec./sec.
13.....	{ Fényi Sept. 6, 1888	.....	2.2	.....
		18	83.3	81.1
		63	175.5	92.2
22.....	{ Tacchini Nov. 16, 1892	.....	4.4	.....
		126	6.6	2.2
		159	28.3	21.7
		228	57.2	28.9
11.....	{ Hale and Ellerman March 25, 1895	.....	115.0	57.8
		217	49.0	70.0
		305	119.0	83.0
5.....	{ Lee Oct. 21, 1914	.....	202.0	83.0
		132	6.7	15.3
		189	22.0	20.8
1.....	{ Pettit May 29, 1919	.....	42.8	20.8
		150	5.5	5.5
		200	14.7	9.5
		319	27.9	13.2
4.....	{ Lee Feb. 18, 1920	.....	60.0	32.1
		410	10.6	8.0
		164	18.6	23.1
7.....	{ Fox May 21, 1907	.....	41.7	23.1
		190	7.5	30.0
		287	37.5	26.7
6.....	{ Slocum March 25, 1910	.....	64.2	127.5
		68	6.1	25.3
		174	31.4	22.2
9.....	{ Evershed May 26, 1916	.....	216.6	124.9
		228	191.7	127.5
		500	216.6	124.9

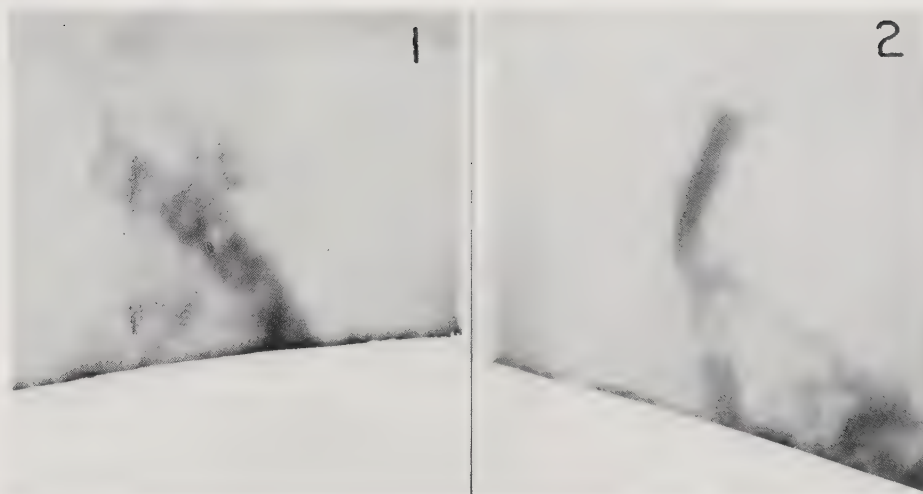
nences. Unfortunately, there is as yet no material available for a comparison of spectroheliograms of an eruptive prominence taken simultaneously in hydrogen and calcium lines. If its whole momentum were divided with a hydrogen atom whose mass is 1845 times as great, the electron would be capable of producing changes of velocity, greater than those observed, by a single impact.

There is at present no positive evidence of the existence of these periodic showers of electrons referred to above, and such a hypothesis must be considered as only a tentative possibility.

August, 1920

END OF VOLUME III

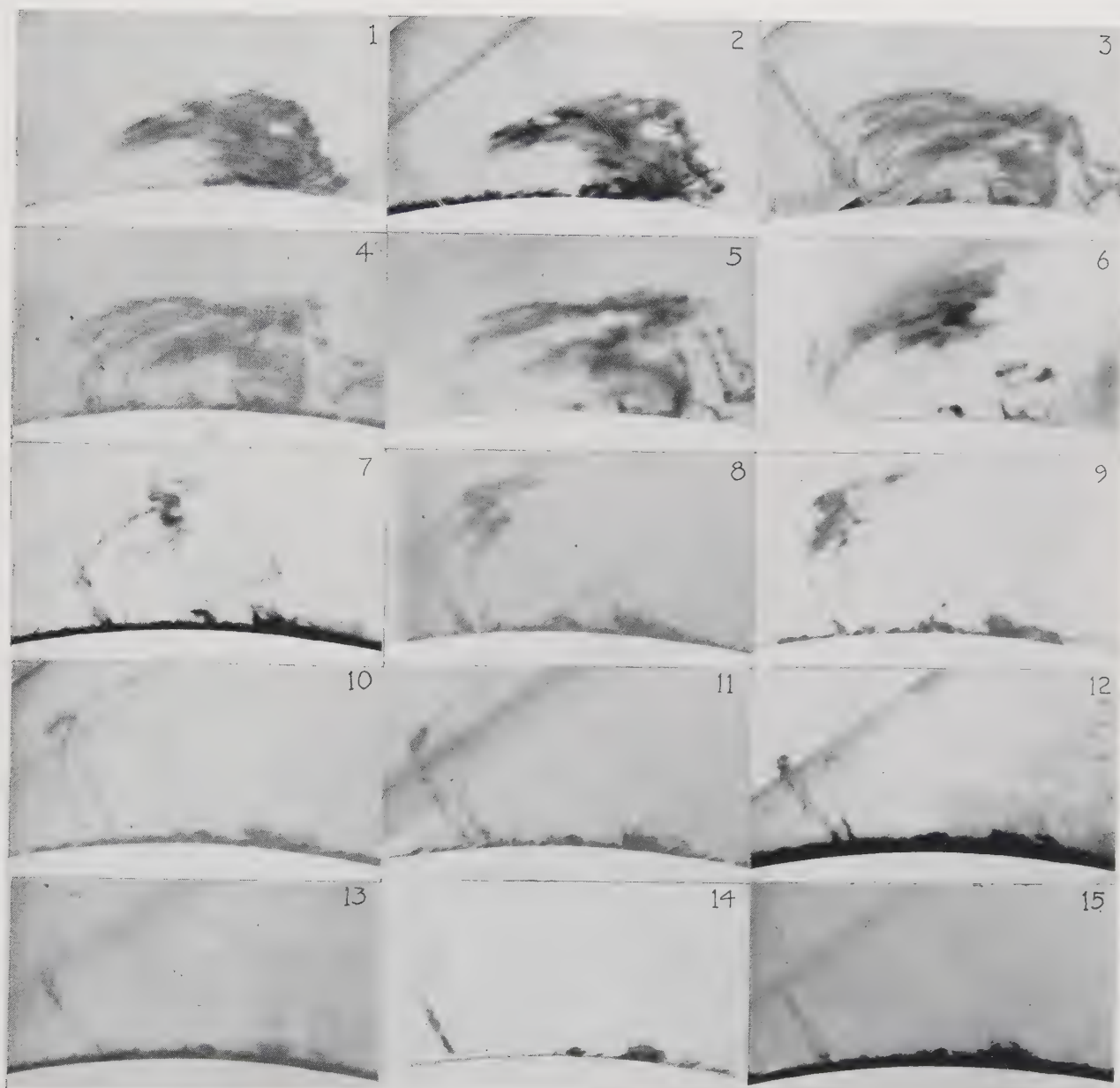
PLATE XXVII



TORNADO PROMINENCES

(1) October 15, 1910; (2) July 12, 1919

PLATE XXVIII



THE "SIGMA" PROMINENCE OF SEPTEMBER 23, 1919

The G.M.T. of exposures were as follows:

(1) 4 ^h 50 ^m 40 ^s	(2) 4 ^h 55 ^m 40 ^s	(3) 6 ^h 00 ^m 52 ^s	(4) 6 ^h 04 ^m 19 ^s	(6) 6 ^h 12 ^m 45 ^s
(6) 6 34 07	(7) 6 42 32	(8) 6 52 05	(9) 6 56 09	(10) 7 00 19
(11) 7 04 45	(12) 7 09 05	(13) 7 11 48	(14) 7 17 30	(15) 7 26 30

PLATE XXIX



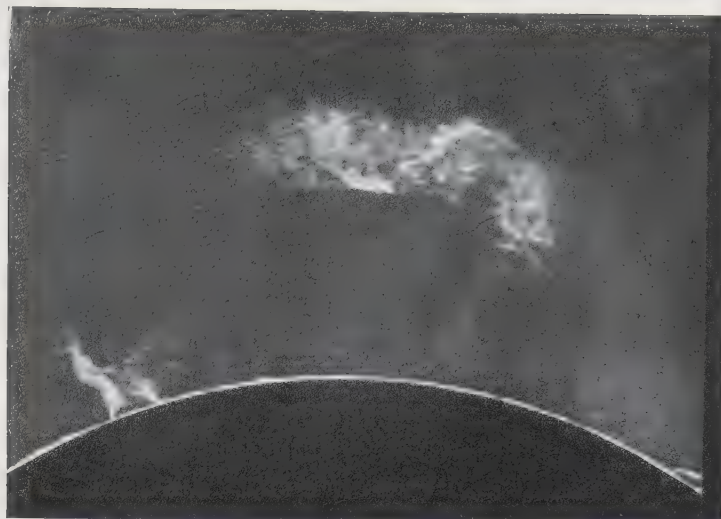
THE "ROCKET" PROMINENCE OF OCTOBER 6, 1919

The G.M.T. of the exposures were:

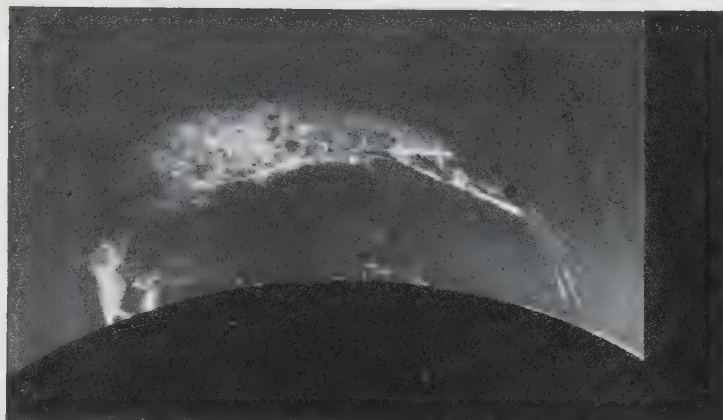
(1) 4 ^h 15 ^m 18 ^s	(2) 4 ^h 39 ^m 21 ^s	(3) 4 ^h 57 ^m 12 ^s	(4) 6 ^h 24 ^m 34 ^s
(5) 6 39 27	(6) 6 45 16	(7) 6 57 05	(8) 7 07 05
(9) 7 16 02	(10) 7 30 26	(11) 7 41 53	(12) 8 09 14

PLATE XXX

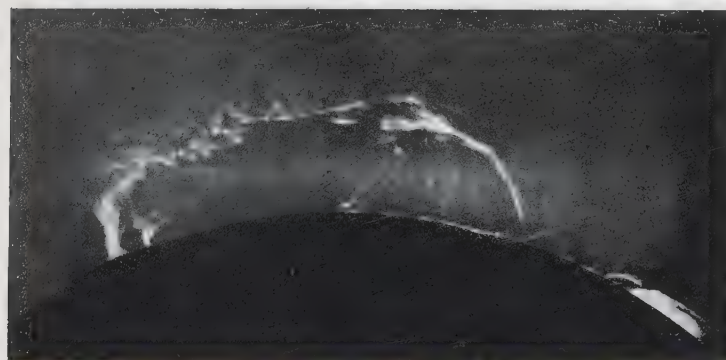
c
G.M.T.
5^h32^m41^s



b
2^h56^m56^s



a
1^h41^m16^s

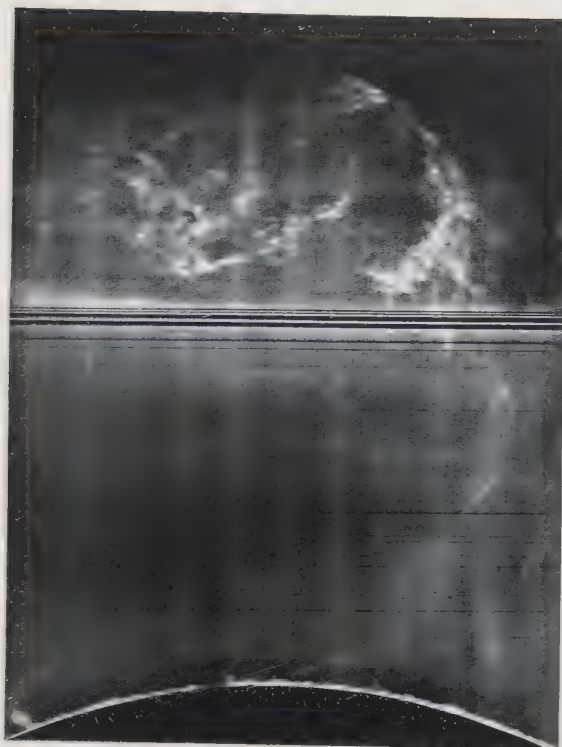


THE GREAT PROMINENCE OF MAY 29, 1919

Scale: for *a*, 1 mm = 9326 km; for *b* and *c*, 1 mm = 8416 km

PLATE XXXI

6
G M T
MAY 29 1919



4
G M T
MAY 29 1919

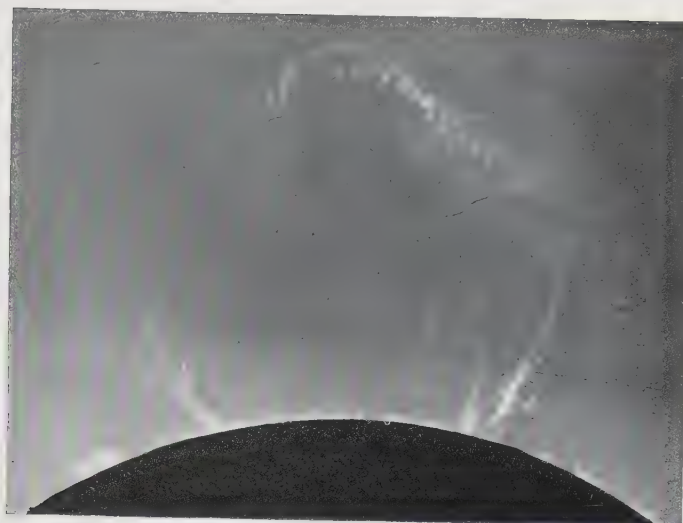


THE GREAT PROMINENCE OF
MAY 29, 1919

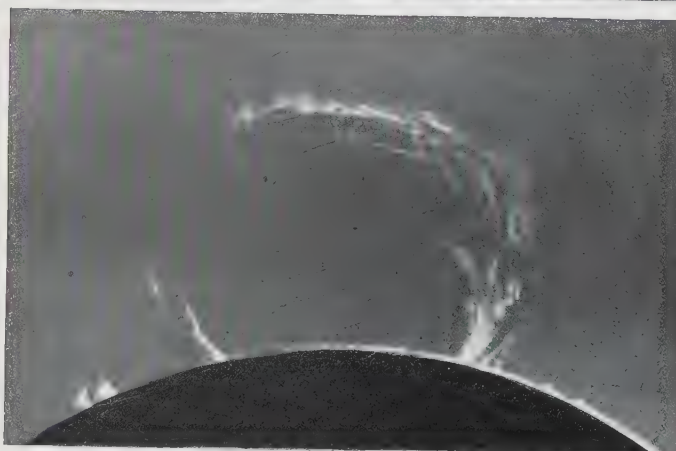
Scale: 1 mm = 8416 km

PLATE XXXII

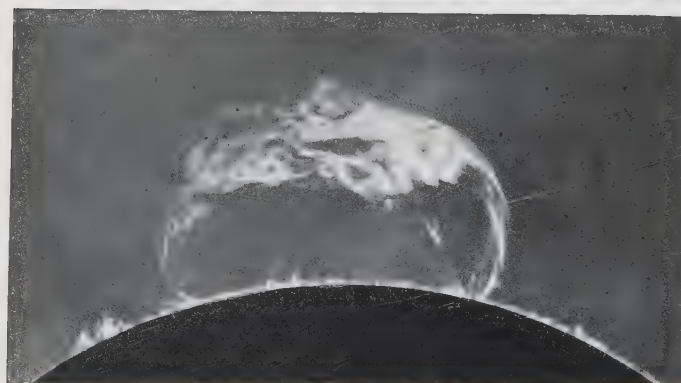
h
G.M.T.
 $4^h 7^m 19^s$



g
 $3^h 51^m 56^s$



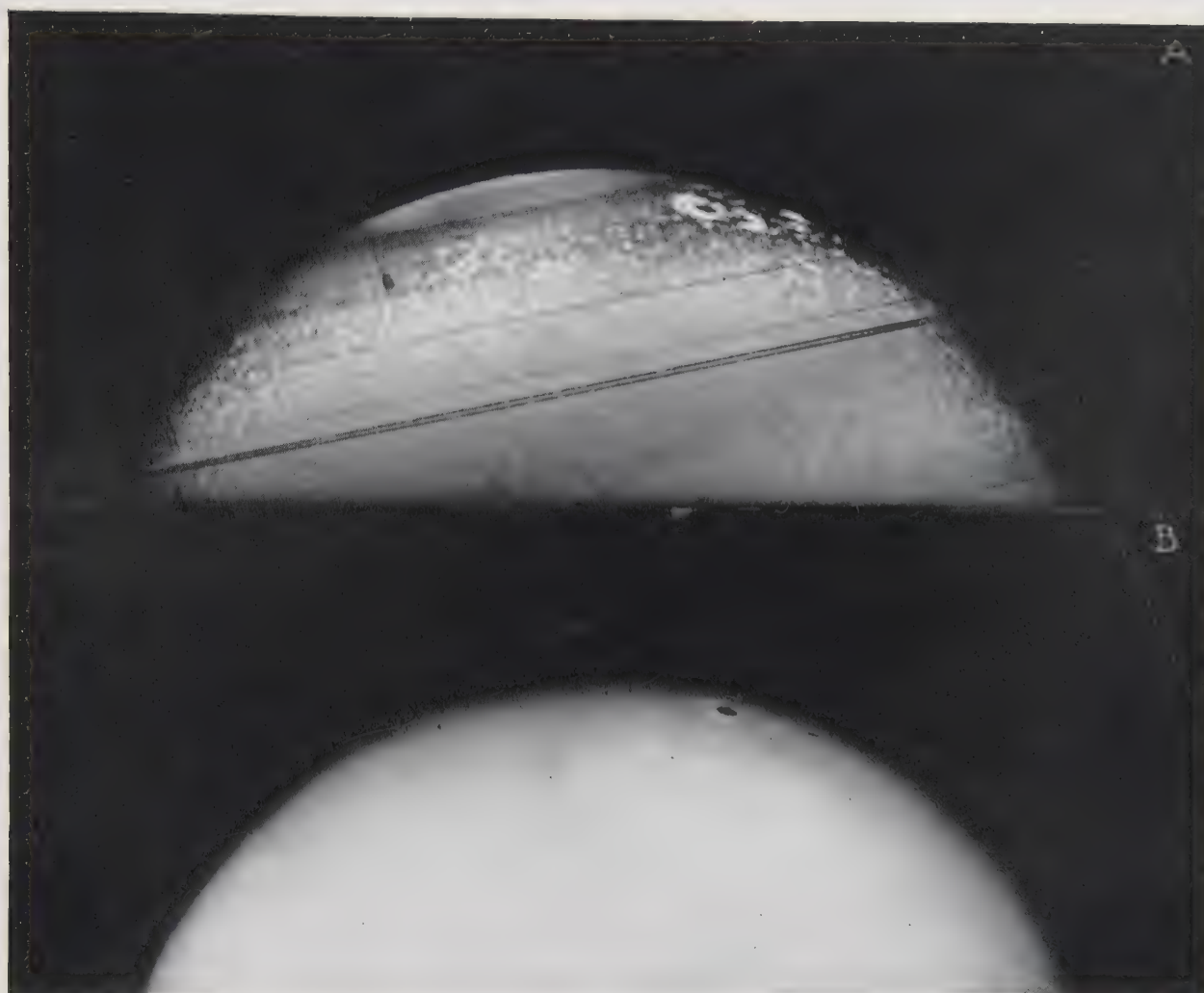
f
 $3^h 50^m 2^s$



THE PROMINENCE OF JULY 15, 1919

Scale: 1 mm = 9572 km

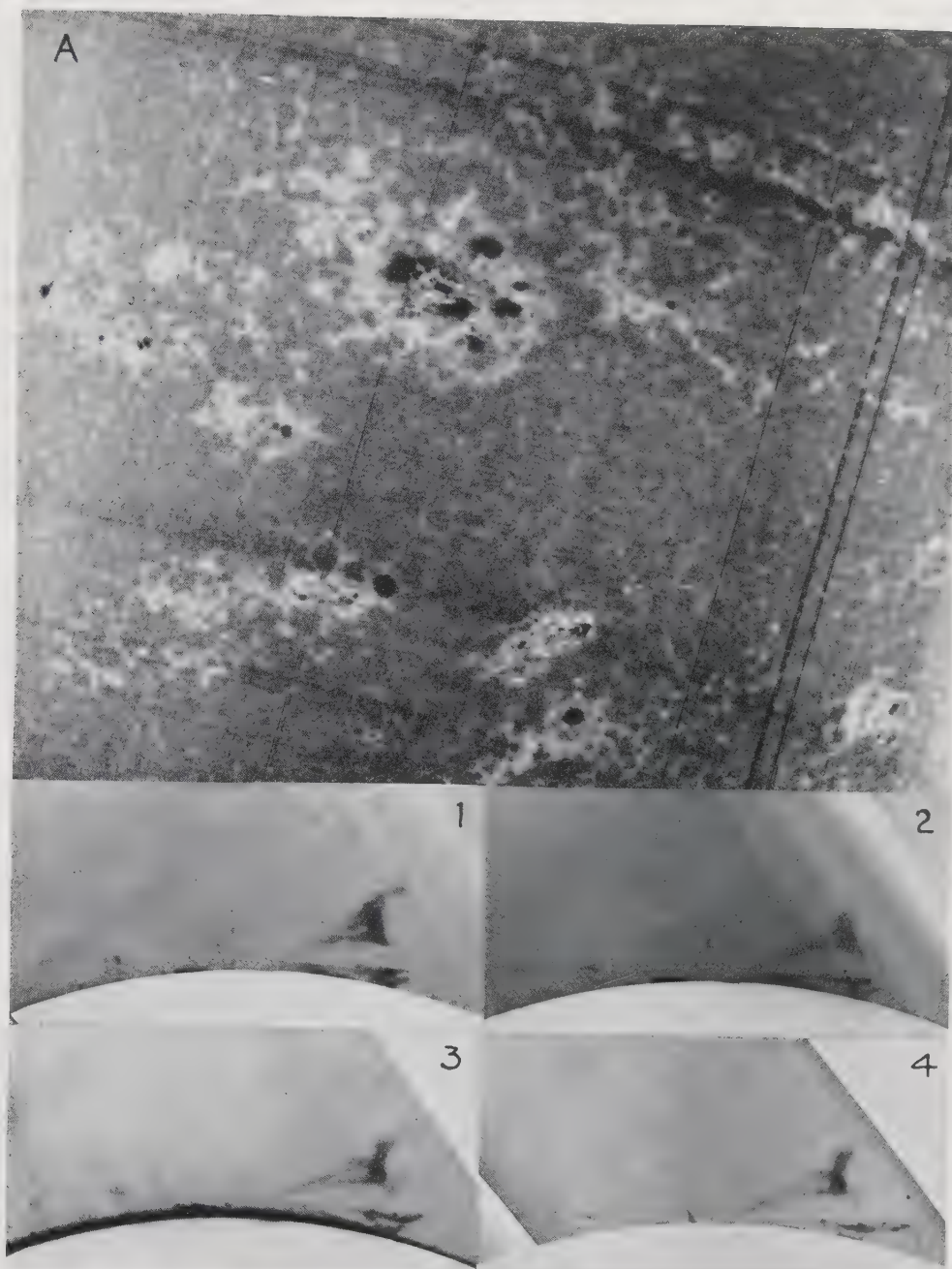
PLATE XXXIII



SUN-SPOT CONNECTED WITH THE GREAT ERUPTIVE PROMINENCE
OF MAY 29, 1919. EXPOSURES MADE ON MAY 30

(A) Calcium spectroheliogram, (B) direct photograph

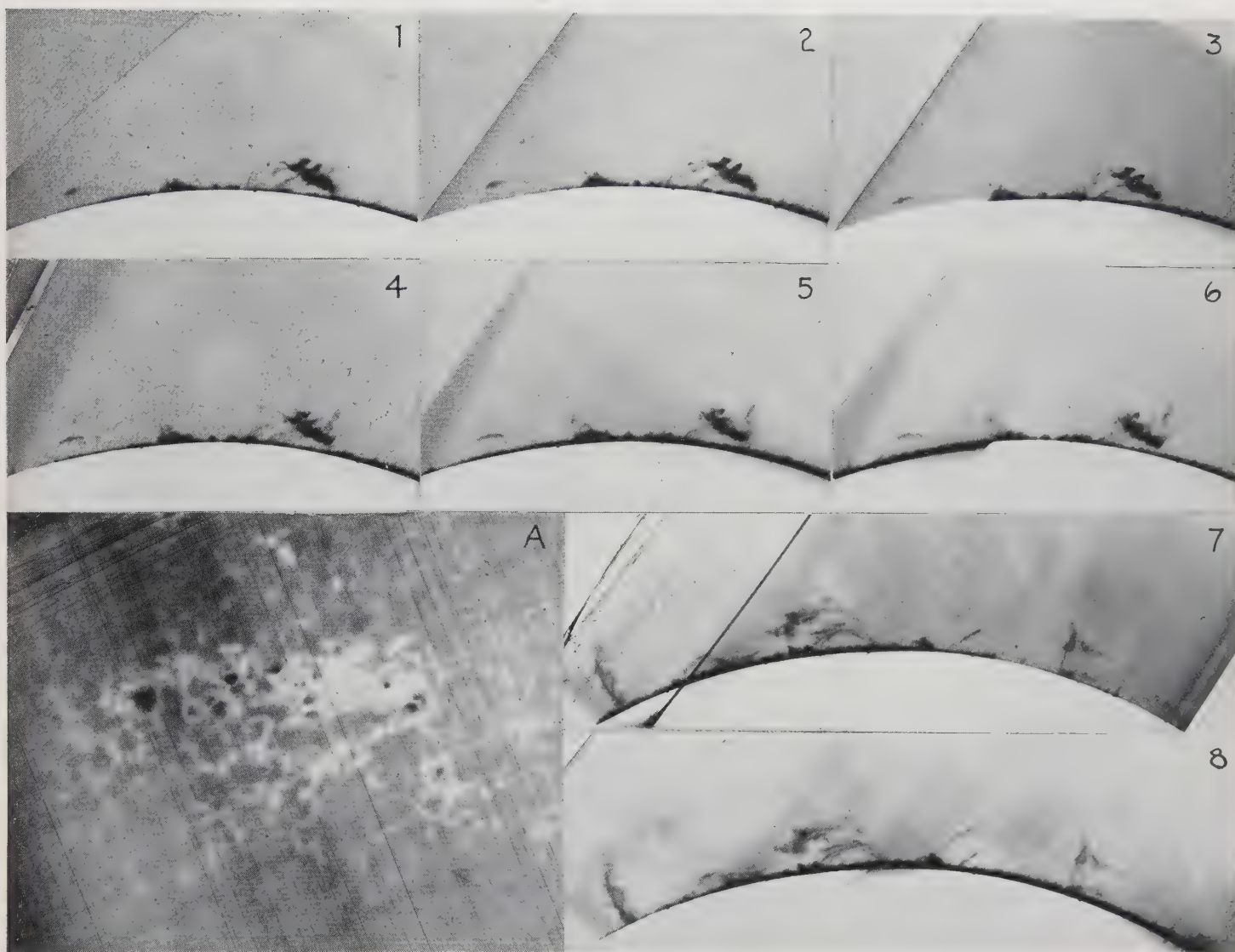
PLATE XXXIV



(A) CALCIUM SPECTROHELIOGRAM OF THE GREAT SUN-SPOT
OF AUGUST 9, 1917

Scale, sun's diameter = 178 mm. Below are four exposures on the prominence which appeared over the spot when it came to the western limb of the sun on August 17, at G.M.T. (1) 4^h59^m37^s, (2) 5^h01^m55^s, (3) 5^h18^m20^s, (4) 5^h25^m45^s.

PLATE XXXV



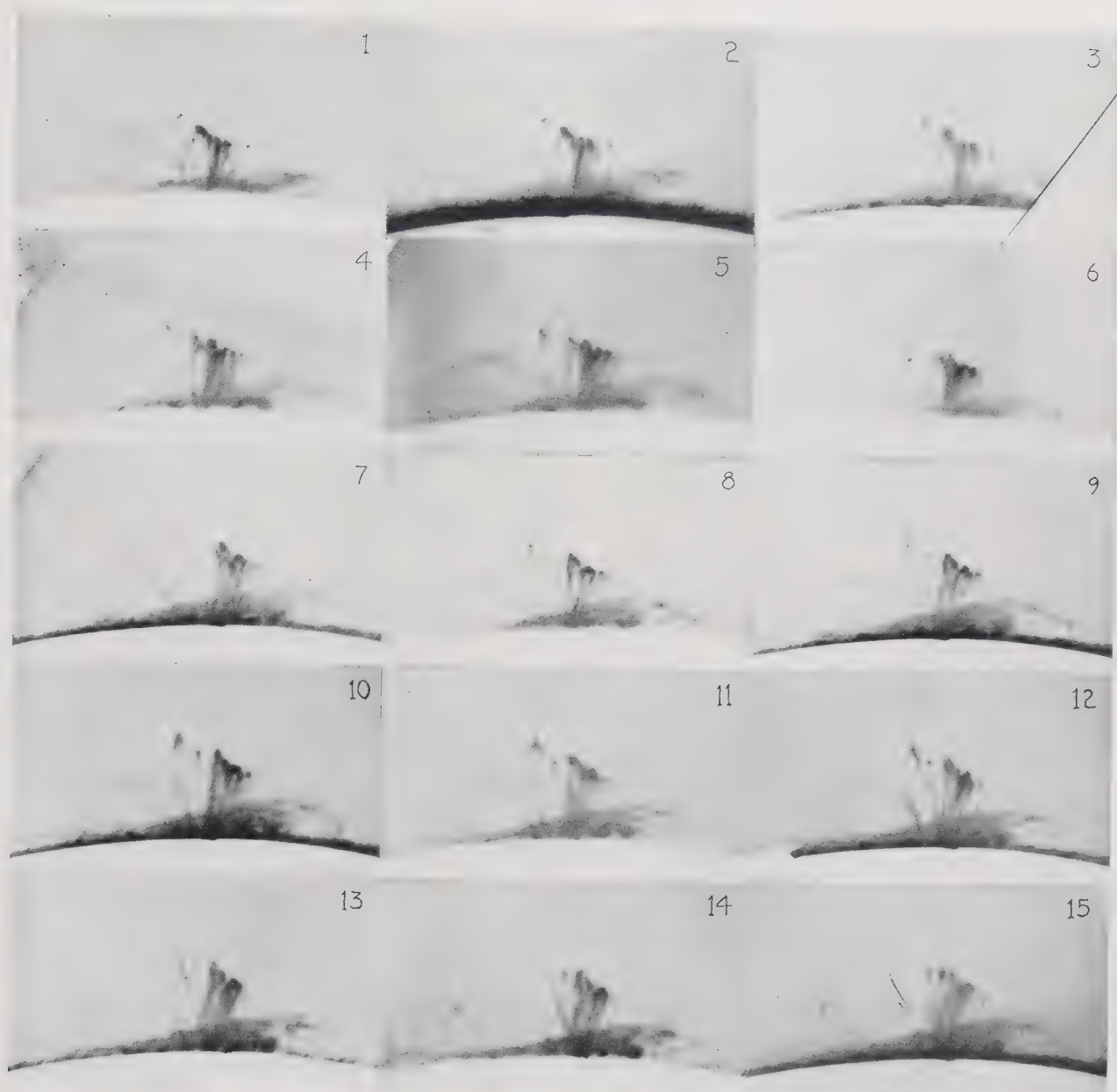
(A) CALCIUM SPECTROHELIOGRAM OF THE GREAT SPOT
OF MARCH 20, 1920

Scale, sun's diameter = 182 mm. Above are six exposures on the prominence which appeared over the spot when it came to the western limb on March 27 at the following G.M.T.:

(1) 5^h28^m46^s (2) 5^h30^m52^s (3) 5^h33^m50^s (4) 5^h37^m14^s (5) 5^h40^m15^s (6) 5^h42^m50^s

Note the eruption from the suspended cloud. Below are given two exposures on a prominence over the same spot on March 29 at (7) 9^h24^m24^s, (8) 9^h28^m15^s.

PLATE XXXVI



PROMINENCE OF SEPTEMBER 22, 1919, WHICH APPEARED
OVER A SPOT ON THE LIMB

The G.M.T. of the exposures were:

(1) 6 ^h 33 ^m 48 ^s	(2) 6 ^h 36 ^m 09 ^s	(3) 6 ^h 37 ^m 50 ^s	(4) 6 ^h 59 ^m 38 ^s	(5) 7 ^h 04 ^m 49 ^s
(6) 7 09 38	(7) 7 14 38	(8) 7 19 50	(9) 7 24 46	(10) 7 30 11
(11) 7 34 46	(12) 7 39 52	(13) 7 44 45	(14) 7 49 42	(15) 7 54 50

PLATE XXXVII



PROMINENCE OF MAY 9, 1911

Exposures made at G.M.T. (1) 4^h45^m54^s, (2) 4^h47^m06^s

